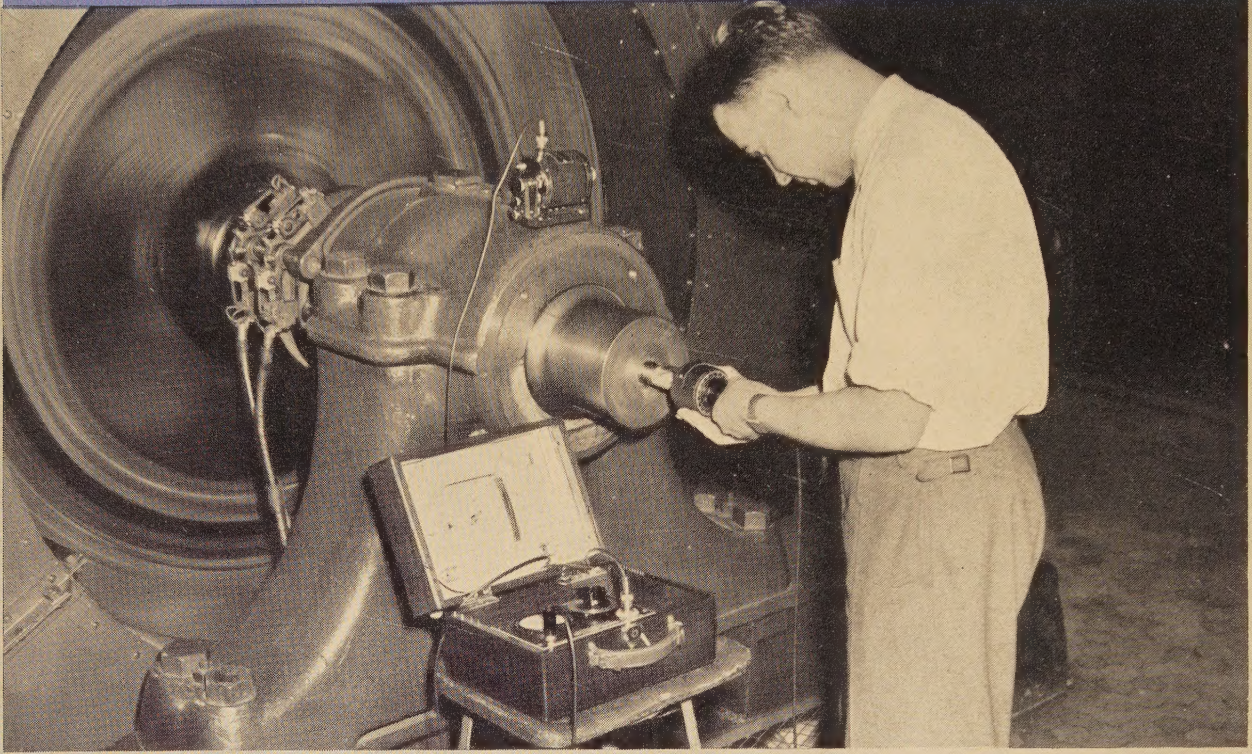
Electrical Engineering

June
1940

AIEE Summer Convention, Swampscott, Mass., June 24-28, 1940

To Measure—BALANCE
ELECTRICALLY



HOW simple would you say it is to balance a 50-ton alternator rotor moving at 3600 rpm until its vibration is less than three ten-thousandths of an inch—or one-tenth the diameter of a human hair? Not very, you say? Well, a little while ago you may have been right. Today you're wrong.

For while heretofore the balancing of large rotating machines was a long, drawn-out procedure, perhaps requiring the removal of the rotors from the machines, now there is a portable G-E instrument that does the job simply, quickly, and under actual operating conditions. And on a 20,000-kva synchronous condenser, for example, balance can be achieved with as few as three runs—which is a far cry from the 100 to 170 trials which were frequently necessary before.

In simple terms, the balancer consists of a hand-held sine-wave alternator, a vibration pick-up, and an instrument. These provide the essential measurements, which are made both before and after trial weights have been placed in chosen balancing planes. By interpretation of the facts thus obtained, almost perfect balance of the machine can be achieved.

Here, then, is another portable, precise, electric instrument for the measurement of a nonelectrical quantity. It joins the ranks of G-E instruments developed to measure the surge of lightning, the trickle of electrons in a vacuum—instruments to analyze color exactly and to unscramble and measure sound waves.

The contributions of G-E engineers to its development were made possible by years of research and a half-century of experience in every field of electrical endeavor. And yet they represent no more dramatic achievement, really, than that of providing accuracy and dependability in the complete line of G-E instruments for the measurement of electrical quantities—current, voltage, resistance, watts, frequency, power-factor—in dozens of styles, indicating and recording, and in ratings to fill every need. That's why, if your problem involves measurement, you should remember General Electric, Schenectady, New York.

HEADQUARTERS FOR ELECTRICAL MEASUREMENT

GENERAL ELECTRIC

430-160

Electrical Engineering

Registered U. S. Patent Office

for June 1940—

The Cover: The New Ocean House at Swampscott, Mass., headquarters for the 1940 AIEE summer convention, June 24–28.

Transactions Section *(Follows EE page 258; a preprint of pages 321–68 of the 1940 volume)*

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¶ Correspondence is invited on all controversial matters.

High Lights • •

Culture in Engineering. Culture must develop mental flexibility, a sympathy with the viewpoint of people of divergent interest, and an understanding of where one's own vocation fits into the interest of the society to which it is at the most only ancillary. This is one of the thoughts expressed by an AIEE past president in discussing the general subject (*pages 229–31*).

Trends in Electric-Power Apparatus. Much of the development in electrical apparatus can be traced to research and to the close co-operation between manufacturers and users who have had the courage to try new and promising ideas, according to an engineer of one of the larger manufacturers (*pages 221–6*).

Engineers and Unionization. Whether or not an engineer shall join a union is a question that each individual must answer for himself, but engineers who develop habits of thinking in connection with their work as prescribed by the union code would be in grave danger of self-disqualification as professional men, in the opinion of one prominent AIEE member (*pages 227–8*).

Contact Phenomena. The closing and opening of contacts carrying weak currents, such as those in telephone switching circuits, involves the generation of high-frequency transients that may eventually cause erosion of the contact metal because of the many operations that are made during the life of the contact, even though the duration of the phenomena may be only a few microseconds at each operation (*Transactions pages 360–8*).

Local AIEE Activities. The annual report on AIEE Section and Branch activities for the fiscal year just ended shows that three new Sections were organized and one new Branch authorized during the year, making a total of 70 Sections and 121 Branches. During the year the attendance at 701 Section meetings and 1,346 Branch meetings totaled 91,949 and 64,972, respectively (*pages 250–3*).

Temperature Rise. Electrical apparatus exposed to the sun's rays may have an additional temperature rise of as much as 20 degrees centigrade, but a wind velocity of a few miles per hour may compensate for this by increasing cooling by convection (*Transactions pages 338–45*).

Arc-Backs. Studies of arc-backs in mercury-arc rectifier tubes by an oscillograph with a "memory" indicate that arc-backs may occur throughout the whole inverse period rather than only at the transition from the normal conducting to the normal insulating state (*Transactions pages 345–7*).

Summer Convention. Ten technical sessions, one general session, and seven technical conferences comprise the scheduled technical program of the AIEE 1940 summer convention to be held at Swampscott, Mass., June 24–28. The summer convention committee is endeavoring to take full advantage of the location by providing ample opportunity for sports and recreation (*pages 248–50*).

Suburban Power Supply. Increased capacity to meet a growing load was provided on the suburban power supply system of a large eastern metropolitan power company by raising primary voltage from 13 kv to 33 kv. Single-line single-transformer-bank substations are used in lightly loaded areas, including many pole-type and factory-assembled substations (*pages 234–8*).

High-Voltage Laboratory. Scheduled functions of the new high-voltage laboratory of the National Bureau of Standards include: X-ray and nuclear-physics studies; precise calibration of voltage transformers; testing of insulating materials; and research and development on methods of measurement at high voltages (*pages 238–40*).

Room Noise. Supplementing the results previously reported in ELECTRICAL ENGINEERING, an article in this issue reports additional data obtained on a continued survey of room noise at various types of locations (*pages 232–4*).

Response Indicator. A new indicator for the performance characteristics of communication circuits shows the change of phase angle between input and output voltages, as well as the change in magnitude, by the shape of patterns on the screen of a cathode-ray tube (*Transactions pages 355–7*).

Lightning Arresters. Performance values which may be expected of present-day commercial station-type lightning arresters rated from 3 to 245 kv have been prepared by the AIEE lightning-arrester subcommittee (*Transactions pages 347–8*).

Textile Machinery. Tests previously reported to establish the characteristic power requirements and to derive an empirical formula for horsepower for spinning machines have been continued for a 216-spindle frame (*Transactions pages 336–8*).

Wire Corrosion. Fine copper wires in coils sometimes fail from what appears to be corrosion, and various causes based on inference have been suggested. Investigation now indicates that cellulose is the source of the trouble (*Transactions pages 357–60*).

Upper-Air Soundings. Airplanes have been supplanted by unmanned balloons for gathering meteorological data with the production of an instrument-controlled radio transmitter for relaying pressure, temperature, and humidity indications to the ground from altitudes as high as 25 kilometers (*Transactions pages 321–8*).

Current Measurement. Current is an essential factor in the complete specification of spot-welding conditions, but its measurement is complicated by the short duration of flow, wave shape, and other factors; a variety of proposed methods were compared in the course of a research program (*Transactions pages 349–54*).

Lightning Protection. Reconstruction of 60 miles of wood-pole line to use the inherent insulation of the wood together with the provision of lightning protector tubes on one of three phase wires has reduced lightning outages more than 90 per cent (*Transactions pages 328–35*).

Correction. In equation 3, page 189 of AIEE TRANSACTIONS (March section) a factor n was omitted from the exponent of ϵ. The equation should be:

$$\frac{\theta}{\phi} = 1 - \frac{\epsilon^{\frac{-2\pi n t}{T_0}}}{\sqrt{1-n^2}} \sin\left[\frac{2\pi t}{T_0}\sqrt{1-n^2} + \sin^{-1}\sqrt{1-n^2}\right]$$

Coming Soon. Among special articles and technical papers now undergoing preparation for early publication are: an article on the subject of the ionosphere by K. K. Darrow; an article discussing some of the current problems faced by modern rail transport by A. M. Wright (A'27); an article discussing the high-speed motion-picture camera as a tool in electromechanical design by J. R. Townsend; an article outlining a method of selecting the size of distribution transformers by M. F. Beavers (A'31); a paper on the application of traction motors by F. E. Wynne (F'20) and G. M. Woods; a paper on co-ordination of power and communication circuits for low-frequency induction by J. O'R. Coleman (M'29) and H. M. Trueblood (M'25); a paper describing a new postgraduate course in industry in high-frequency engineering by A. R. Stevenson, Jr. (F'37) and Simon Ramo; a paper on lightning currents in arresters at stations by I. W. Gross (M'40) and W. A. McMorris (M'37); a paper discussing enclosed spark gaps by W. E. Berkey (M'39); papers on the impulse strength of cable insulation by C. M. Foust (M'31) and J. A. Scott (M'34), and E. W. Davis (F'34) and W. N. Eddy (M'29); a paper on electric power for airplanes by W. J. Clardy; a paper on the accuracy of watt-hour meters on intermittent loads by M. A. Faucett (M'35), C. A. Keener (M'28), and M. S. Helm; and a paper on watt-hour meter performance with power rectifiers by C. T. Weller (M'21), H. E. Trekell (A'35), and F. O. Stebbins (M'39).

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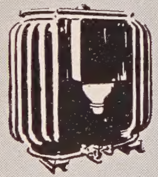

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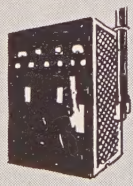
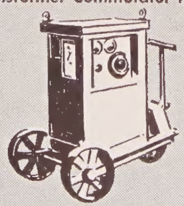


INDUSTRIAL POWER RECTIFIERS
Electronic Tube Type



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AMERTRAN

Trends in Electrical-Apparatus Development

A. C. MONTEITH
ASSOCIATE AIEE

A brief survey of significant developments in apparatus for the generation, transmission, and distribution of electric energy

DEVELOPMENTS in electrical apparatus might be compared with the saying "From the acorn comes the mighty tree." Likewise, the growth of the electrical industry can be compared with the growth of the tree into a forest. The acorn might develop into a great tree or be choked out by stronger trees or thoughts, but always the forest is increasing in coverage. When we examine the development of electrical apparatus we find a large number of thoughts that have not matured, whereas some one thought may have been the nucleus of a complete industry.

As the subject of this article, one part of the "forest" has been selected for a brief survey of the developments—the generation, transmission, and distribution of electric energy.

A Westinghouse catalog dated 1888 set forth in glowing terms the great strides that had been made in the development of generating equipment. The fact that dynamos could be offered that would supply 3,000 lights was an achievement; station switches were simple fused knife switches; and the very efficient lightning arrester consisted of nothing more than a saw-toothed gap in air. When we look back, we see that this was the start of the electrical industry. Today we have generators capable of supplying 8,000,000 lights; we have circuit breakers that will interrupt several million kilovolt-amperes in place of knife switches; and we have highly developed lightning arresters that will handle a direct stroke of lightning and clear a circuit of up to 287 kv operating voltage.

Much of the development can be traced to research and to the close co-operation of the manufacturers and users who have had the courage to try out the new and promising ideas. In a large number of cases we find the old adage "necessity is the mother of invention," has influenced some of the particular points of attack and selected some of the paths that we have followed.

GENERATION

The necessity for more economical generation, in order to promote the industry, has meant a continuing change in power-station design, but it has certainly secured results. Thirty years ago the average coal consumed to produce a kilowatt-hour of electricity was 5.4 pounds. Twenty years ago it was 3.3 pounds, and today a modern base-load station of 100,000-kw capacity can produce a kilowatt from 0.86 pound of coal—less than one-sixth the amount used a generation ago. Many factors have contributed, some of which are, higher inlet pressures and temperatures, and larger units or combinations of units. This trend in temperatures and pressures is very strikingly illustrated in figure 1. In the 30 years mentioned, the pressure has gone from 275 to 1,250 pounds per square inch and there is now under construction a station to use 2,400 pounds. The inlet temperature has been increased from 600 to 950 degrees Fahrenheit in this time.

Great credit is due the boiler manufacturers for the tremendous advances in steam generation. Rapid strides also have been made in the increase of size and speed of turbine-driven machines. Research has made possible the building of larger 3,600-rpm machines now than were available at 1,800 rpm in 1925. Today we are building an 81,250-kva 3,600-rpm machine. All this can be attributed to developments in metals as well as the improvement in efficiency and methods of dissipating losses—all triumphs of research. Figure 2 illustrates the trend in the size of machines operated as units. An examination of the ratings of machines purchased in the last five years indicates a trend more toward smaller and higher-speed units placed closer to load centers. Some of the trend to the smaller generators might also be traced to the fact that many of them are superimposed machines. Actually, the combination of the superimposed and low pressure units sometimes results in a fairly large operating unit.

Figure 3 is an artist's conception of the 81,250-kva 3,600-rpm machine, the largest yet undertaken. It illus-

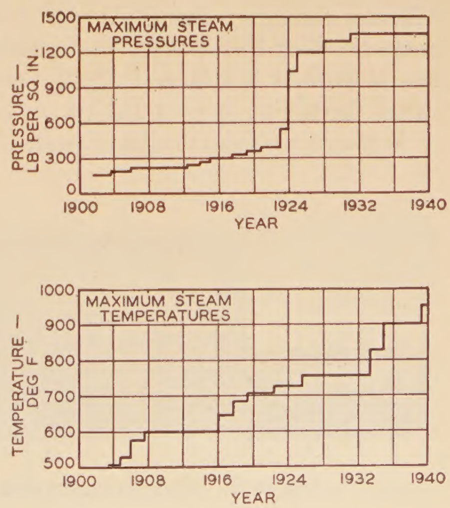

Figure 1. Trend in maximum turbine inlet pressure and temperature

Essential substance of a paper presented at meetings of the AIEE Philadelphia Section, October 9, 1939; Memphis Section, April 15, 1940; St. Louis Section, April 17; and Wichita Section, April 19.

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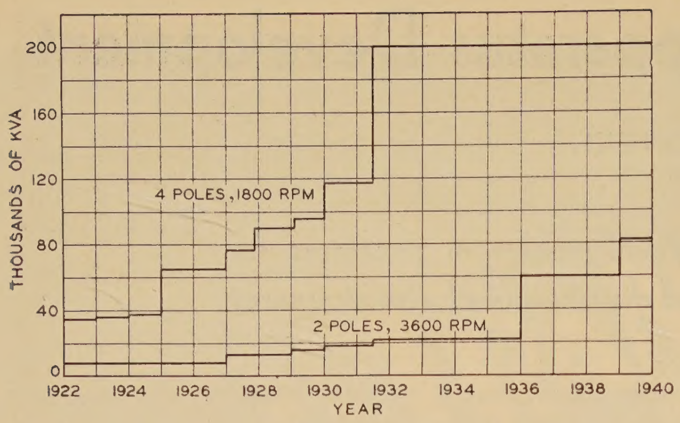


Figure 2. Trend in maximum size of 60-cycle two- and four-pole turbine generators operating as units

trates three trends: the increasing size of 3,600-rpm machines, already discussed; the use of hydrogen as a cooling medium; and the effort to improve appearance. The trend to hydrogen-cooled machines has been very pronounced for the larger high-speed machines. Hydrogen is a very efficient heat conductor and is lighter than air; therefore the windage losses, which are large in 3,600-rpm machines, are materially reduced. The use of hydrogen has made possible the building of generators approaching 99 per cent efficiency. In the last five years, 95 per cent of the units to which hydrogen-cooling is economically suited, have been so cooled.

The question of appearance has received the undivided attention of the manufacturer and user. In order to improve the appearance of the machine and blend the different parts into a pleasing assembly, preliminary artist's drawings are prepared for the larger machines before work is started on the final design. This gives some idea of the appearance of the completed machine when installed. Any one familiar with the earlier machines will readily see the contrast of how corners are rounded, how unsightly piping, valves, and gadgets are concealed, and how the whole is blended into a finished-looking machine. For example, the first designs of hydrogen-cooled machines had the water box of the cooler exposed as well as the connecting piping. This has been completely enclosed with a housing that blends with the lines of the main machine. Likewise the direct-connected exciter has been built in an enclosure that blends with the machine lines. Figure 3 also illustrates the largest 3,600-rpm exciter yet undertaken, having a rating of 250 kw.

Although such drawings are made and models are built of the larger machines, appearance is not overlooked in the smaller machines. In other words, we are no longer just designing a piece of apparatus to produce so many kilowatts, but we are now designing a piece of apparatus that will produce these kilowatts and also blend into a station design in a pleasing manner.

Although the improvement in efficiency of steam generation has restricted the field of economical water-power developments, there is still a demand for even larger water-wheel generating units. Figure 4 shows the trend in size of water-wheel-driven machines. The 108,000-kw Grand Coulee machines are the largest in size and rating yet undertaken. Appearance has also been improved in the design of this class of machine.

TRANSMISSION

In all branches of the transmission of power there has been a concentrated effort to obtain a clearer and better understanding of the fundamentals. Following the World War, increased loads necessitated working existing lines to the limit. Some failed under the strain so that consideration was given to reasons and methods of overcoming the difficulties. Stability of systems became a much discussed problem, and methods were presented to calculate the performance of lines. Stability has been a much used word in connection with transmission of power, and we find many definitions in the printed matter. Although the analytical methods of calculating the performance of systems are well understood, the problem is very tedious and sometimes impossible of solution, especially with the more complicated systems having many generating stations.

At the same time that stability was a problem to the utility companies, a large number of railway networks also was being considered in the United States, and the calculations for this class of service were practically impossible. As a result of these difficulties the a-c network calculator was devised as a means of setting up systems in miniature, placing different types of faults on the system, and allowing a recording of the results of various switching operations. In other words, the system is set up in miniature and operated as the actual system would be in practice, with the pleasing advantage that faults can be applied and switches can be opened and closed at will without jeopardizing the service such as would be the case if tests were run on the actual system. This tool greatly simplified the calculations of complicated networks and made possible studies that previously could not have been undertaken. The network analyzer has been in operation

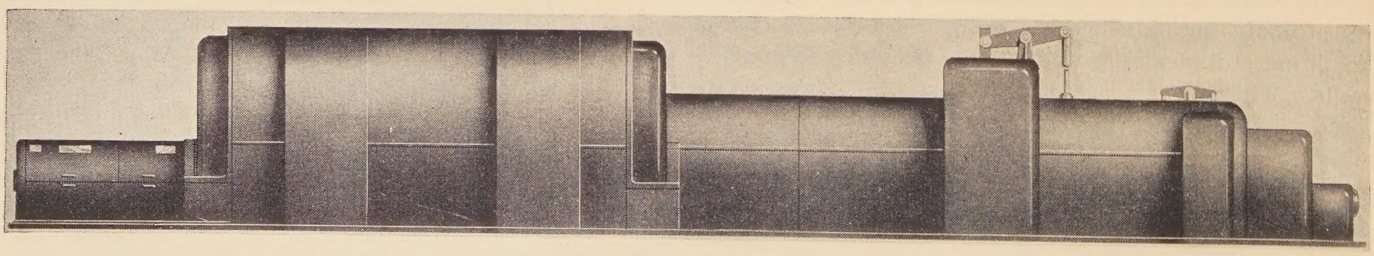


Figure 3. Artist's conception of an 81,250-kw 3,600-rpm turbine, illustrating improved appearance

Figure 5. The network calculator, a means of operating the planned system

for ten years, and more than 200 systems have been studied for practically all the ailments that could possibly exist in an electrical system. The use of this calculator is now the universally accepted method of making a study on a complicated system. During the past ten years the utility of the calculator has been broadened. It has been used for new and interesting problems, one of which, the application of the De-ion protector tube, is directly connected with the transmission problem.

The De-ion protector tube is a device that is placed in parallel with line insulation. When lightning strikes the line the surge current flows through the tube instead of the insulator. At the time of breakdown the tube is virtually a short circuit on the line. To function properly it must become an insulator before the oil circuit breakers controlling the line are tripped out. We know that arcs in contact with certain materials, cause them to give deionizing gases. These try to extinguish or deionize the arc at or close to current zero. We also know that when a short circuit is applied to a system and is removed the system voltage goes to a low value and then recovers at a rate depending on system line characteristics, transformers, loads, and other factors. Whether the arc will extinguish or not depends on the rate at which the system recovery voltage tends to maintain the arc path as contrasted to the rate at which the deionizing action tends to build up dielectric strength. If the dielectric strength recovers faster, then the arc is extinguished. If the system voltage recovers faster, then the tube restrikes. Thus we have a race between these two opposing factors and the problem is to predict the results before actually running the race.

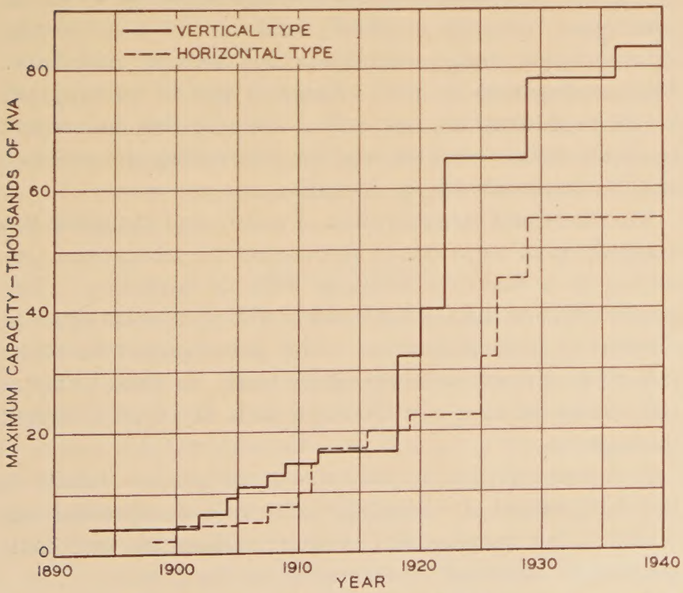


Figure 4. Trend in maximum water-wheel generator ratings

Laboratory tests will give the dielectric recovery of tubes, one factor in the race, but it is difficult to take a system and test it for all the possible variables to obtain a true picture of the system recovery voltage, or the other factor in the race. Here again the network calculator made possible a solution to a problem that heretofore had not been undertaken in a broad way.

The satisfactory application of the De-ion protector tube has allowed the design of lines that are practically lightningproof, and has provided a means of rehabilitating lines already built but vulnerable to lightning outages.

This raises the question as to what is our present knowledge of lightning and what we know about protecting lines and equipment against it. The desire for better service not only stimulated the extensive study of stability to provide means for better system operation under fault conditions, but also launched an intense field and laboratory study of the subject of lightning, to see if a large number of these faults could be eliminated by a better understanding of the problem. This work resulted in the direct-stroke theory which revolutionized line design. It is not a question now as to whether or not a lightningproof line can be built because there are several in operation; rather it is a question of refinements to obtain such lines at the lowest possible cost. These refinements require more information on the exact wave shape of the front and tail of the lightning stroke and its magnitude and duration. Schonland in South Africa has done some very fine work and has evolved a theory for the formation of lightning discharges. McEachron in the United States has checked some of the evidence secured by Schonland, and also, in co-operation with the power companies, has secured considerable data on the magnitude of surges. Wagner has now evolved some new instruments that have already proved their worth in securing further data. One of these that has given some very interesting data is described in the succeeding paragraph.

For many years it has been desired to secure a complete graph of magnitude and duration of lightning discharges, but little information is available. Burns on lightning-arrester gaps could only be reproduced in the laboratory by the use of long low-current surges with magnitudes of

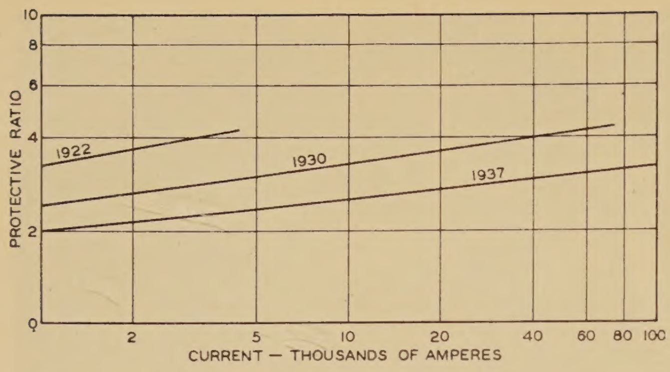


Figure 6. Improvement in lightning-arrester protection

the order of 2,000 to 4,000 amperes and durations up to 3,000 microseconds. In order to secure a complete story of the magnitude and duration, a new instrument, the Fulchronograph, has been built and a large number installed. This instrument has been developed primarily for the purpose of measuring the current in lightning strokes or in apparatus connected to transmission lines through which a current flows that is associated in some manner with the lightning current. Two types have been developed: One, known as the high-speed instrument, measures total intervals of time of the order of one cycle (on a 60-cycle system); the other, or slow-speed instrument, measures current variations having a duration of approximately one second. These devices are arranged to be connected into the circuit and are ready at all times to measure the current without need of tripping the circuit or throwing the switch as a motor drives them continuously. Their operation is based on the principle of storing the current indications in the form of remanent magnetism which is later measured at leisure. In this principle they are similar to the surge-crest ammeter.

A few of the outstanding conclusions from field investigations are that: currents of the order of 100,000 to 200,000 amperes can exist; the probability of surges of low magnitude is much greater than that of high-magnitude surges; long-duration surges of low magnitude can exist; there can be one or several repeated strokes in the space of a few cycles.

How has all this lightning investigation influenced the design of lines and apparatus? As a result of this work economical high-voltage lightningproof lines can be built by the proper use of ground wires. This is a reality. Lines in lower-voltage classes already built or being built have been made practically lightningproof by the application of the De-ion protector tube.

These findings have also influenced lightning-arrester design. Figure 6 shows how the protection ratio of lightning arresters has been lowered. Recognizing the possibility of having to discharge currents of high magnitude, the arresters not only have been made capable of carrying these currents but also have been designed to give protection to the apparatus. If the impulse strength of equipment had a ratio of say 4.0 then it can readily be seen that the improvement in the arrester characteristics is such that the insulation is protected against high-magnitude surge currents. Also the characteristics of arresters of the line type have been changed to be capable of discharging surges of long duration.

STATIONS AND SUBSTATIONS

In high-voltage substation equipment there has been a trend to the use of high-speed reclosing of circuit breakers with times selected to insure maintenance of synchronism of equipment after the operation. Breakers for 132 kv are now available that can reclose a line in less than 20 cycles from the inception of a fault. The limit to which this speed can be carried is dictated by the dead time or open time to allow the arc path of the fault to deionize. On 132 kv this is of the order of 10 to 12 cycles; however, this time plus the opening time of the breaker still allows the reclosing when the operation is on a tie between two large systems. Reclosing would not be feasible when all the power is transmitted, as times shorter than this deionizing time must be secured to maintain synchronism.

Quick clearing of faults on all systems is desirable, and there have been improvements such that standard breaker clearing times are of the order of eight cycles. In order to utilize the improvement in breaker speeds, high-speed relays have become standard equipment on important lines. Relays are now available that will operate in less than one cycle for faults occurring on the greater part of a line section. They may be of the impedance type, carrier-current type where the ultimate in speed is required for long lines, or pilot-wire type for short lines.

What is the trend in circuit-interrupting devices? Circuit-breaker designs and developments are not subject to the same accuracy of refinement of calculations as are some other classes of apparatus where magnetic and electric circuits are more closely defined. Any new idea or radical departure from conventional construction must be thoroughly tried and completely tested to determine its adequacy and performance. This not only adds to the time required for major circuit-breaker developments, but also necessitates the maintenance of very large and expensive laboratory testing equipment.

The great concentration of power in the United States during the last 10 or 15 years severely taxed the forms of switchgear formerly available, and an intensive study of switchgear design and operation became necessary. The development of more efficient types of interrupters for oil-type breakers not only overcame this but made available devices that allowed the remodeling of a number of oil breakers already in operation.

This increased concentration of power also has made the designer more conscious of fire hazard in substations, resulting in a desire for breakers with air insulation. The introduction of the De-ion breaker some ten years ago was the first to meet this desire. This development has been extended, always with complete tests, so that today a 100,000-kw station can be built with dry-type breakers throughout.

A recent addition to the air-circuit-breaker family is the compressed-air breaker, in which compressed air operates the opening and closing mechanism, and compressed-air blasts aid in extinguishing the arcs.

Approximately 2,000 interrupting tests have been made

on a 1,500,000-kva breaker of this type. Single-phase interruptions have been made of currents from 1/4 ampere to 65,300 amperes, with 13.2 kv across the contacts. Cathode-ray and magnetic oscillograms have been obtained throughout the current range. All currents can be interrupted at the first zero with about one-half cycle of arcing. The low-current interruptions do not give rise to overvoltages; throughout the range of test no transient voltage greater than twice normal was observed. The high currents can be interrupted without external flame, and without objectionable noise.

There has also been a very wide acceptance of factory-built-and-assembled switchgear. This idea has been developed to the point that now a complete substation of 1,000 to 2,500 kva is enclosed in a common tank.

In considering the work done on fundamental transformer design, tests made with surge generators showed how to increase the impulse strength 50 per cent by a better arrangement of the insulating structures. Recently it has been found that this strength is increased a further 30 per cent by vacuum filling the transformer. This eliminates all the gases in the windings and, therefore, raises the point at which corona begins to form, which is the starting signal in the failure of an insulating structure in this type of equipment.

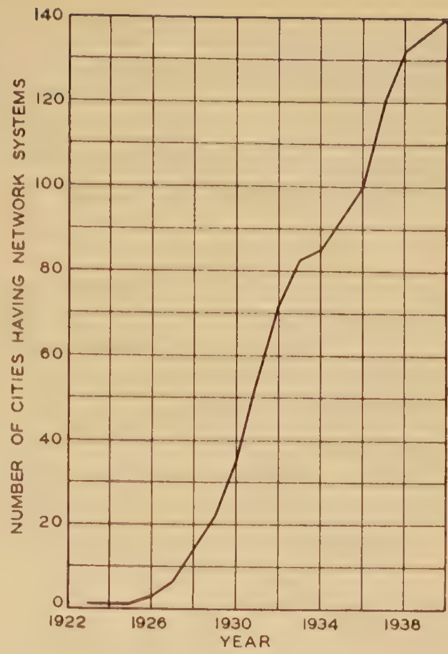
At the same time it has been found that if the oxygen is eliminated from the transformer, greater short-time loads can be carried with the same margin of safety than can be carried by the same transformer operated open to the atmosphere. As a result of these findings, transformers are now being vacuum filled and fitted with equipment to exclude oxygen, or are being sealed so that no air can enter, therefore operating as oxygen-free transformers. The former principle is used in large high-voltage transformers while the latter is used in the transformers of 1,000 kva and less. The development of a relay to permit the loading of transformers by copper temperature allows taking full advantage of these findings.

In all this work we find a decided trend to the impulse testing of transformers. In the case of the *CSP* (completely self-protected) distribution transformer where the protection is incorporated in the design, the completed transformer now gets a final impulse test with a current discharge of 65,000 amperes. The Westinghouse company has impulse-tested approximately 150,000 distribution transformers with approximately 800,000 kva rating and 175 power transformers with approximately 2,100,000 kva rating.

DISTRIBUTION

One of the outstanding trends in the field of distribution has been the increasing use of static capacitors for power factor correction. The hanger-type unit can now be installed for eight or nine dollars per kilovolt-ampere. As a result of this low installed cost, the use of capacitors has grown fast in the last two years. They are now being justified on the basis of releasing system capacity, resulting in an over-all saving in total system investment. This is particularly true on the systems operating with low power factors. When it is realized that 1.3 kva corrective

Figure 7. The trend in the use of the a-c secondary-network system



on 65-per cent-power-factor circuit and 2 kva corrective on a 90-per cent-power-factor circuit will release 1 kw of system capacity, it can readily be seen that this investment of $13 to $20 per kilowatt of released capacity may be readily justified depending on how far back into the system the capacity is released. Improved voltage conditions on primary feeders also may dictate the amount of corrective capacity that can be justified.

The use of the low-voltage a-c secondary network system continues for concentrated load areas, or where reliable service is required. Figure 7 shows the growth of this scheme. It has even been used in the supply system for station auxiliaries in one station and is receiving consideration in a number of others. Its use no doubt will expand.

The desire to eliminate oil in vaults located in buildings or congested areas has led to the use of a noninflammable liquid in place of oil. The Westinghouse company has built over 1,000 of these transformers to date. Precautions must be taken to provide for venting of gases given off if a fault occurs in them, as these gases are noxious. A dry-type transformer has now been designed and a number built for this class of distribution system or for use in industrial or central-station plants where oil is a hazard.

RESEARCH

So much for the apparatus itself. It is of interest to see how many of these developments are dependent on or originated from research ideas. In some manner practically every one can be traced back to some research investigation. Improvement in generating units required extensive research to secure metals that would withstand the high temperatures and stresses met in the larger machines. Research gave us the instruments to conduct our field investigations on lightning which have been so far reaching. Research gave us the ideas on how to produce a dry-type breaker. It gave us the conception of eliminating oxygen from transformers to improve their rating and impulse characteristics. It gave us noninflammable liquids for transformers and insulation for the dry-type

transformers. Thus a review of developments would be incomplete without calling attention to the necessary part of our advancement that is directly traced to research. It emphasizes the necessity of continued research in close co-operation with the operating companies to make possible future reviews of developments.

FUTURE

What of the future? Developments and improvements are fostered by expansion, and I believe that we shall find even greater expansion of the electrical industry than we have had as new uses are found for this servant. For example, when other basic industries were operating at from 30 to 70 per cent of normal we find the electrical industry was operating at a few per cent below normal, and it is now operating well above normal. Although industry in general was not using electricity for production purposes, new uses were found. The domestic load increased through the use of the refrigerator, washing machine, and other laborsaving devices, while air conditioning materially improved the commercial load. This trend has been so marked that system peaks now come on hot Tuesdays in the summer when iron and air-conditioning loads are a maximum rather than during the usual Christmas rush. Also, instead of getting one day with an outstanding peak during the year, a large number of days will show loads very close to peak. Thus as business picks up (and the prospects look better than ever at present) new peaks will be made in the electrical industry. Even a pessimist must agree that there is a very definite future for this industry.

To meet this the electrical industry will produce better and more efficient apparatus. Although the largest 3,600-rpm machine to be built is the 81,250-kva unit now under construction, the designers would not hesitate to build a 100,000-kw unit at this speed. Water-wheel-driven generators are now limited only by manufacturing facilities, so that the industry is now ready to build any size within these limits.

Although there has been no demand for higher transmission voltages, the industry could produce 330-kv apparatus with present design knowledge. All high-voltage lines now being built will be of the lightningproof design and means will be found to make the low-voltage lines lightningproof at a reasonable cost. The quick clearing of faults no doubt will be studied for improvement although with a decrease from 25 cycles to 8 cycles already accomplished with modern interrupting devices, the remainder will be gained at a slower rate.

On account of the improvement in the efficiency of smaller generating units, the trend no doubt will be to placing smaller steam stations close to load centers, thus minimizing transmission costs and losses at the expense of possibly a slight increase in operating charges. These stations will have dry-type breakers throughout and oilless indoor transformers for the auxiliary supply.

In the distribution field the demand for better service will be met with new and improved methods. We find a larger number of companies using the low-voltage a-c network for the heavier load densities and a number trying different schemes for the lighter-density areas.

More and more complete equipment will be factory built, assembled, and tested, making the installation time and expense a negligible part of the cost. In other words, there will be a greater tendency to have equipment thoroughly tested at every point in the manufacturing process so as to insure a well-balanced finished product.

It is only by diligence of thought and the spending of money for investigations and research that we progress, and sometimes the path seems a difficult one. In a talk at the dedication of the American Rolling Mill Company's research laboratory, Doctor C. F. Kettering emphasized this point by an interesting illustration. He admitted that many discoveries were stumbled onto quite by accident, but pointed out that there was a reason for the accident. For instance, he said that if we should shut out the light from a room and place a chair out in the center no one would know where it was; but if some venturesome soul began to walk around in the room he would find the chair; he might stumble over it and skin his shin, but at least he would find it. We can be sure that nobody would find it if everyone sat still and did nothing.

It is apparent from past diligence in all phases of the electrical industry that we are determined to be up and about, groping around, possibly, and to some extent in the dark, but we are not holding back for fear of skinning our shins; we will be quite happy if we don't break a leg.

History of the Electrical Industry

"THERE is no written history of the electrical industry . . . There is under preparation a history of the electric-utility industry, but that naturally can cover but a part of the complete story of electricity. What has been the course of electrical engineering, of design, of generation, of utilization, of construction? We have had a history of lighting, but what of transformers, of motors, or protection, or all the host of things that go to make up our equipment side?

"Why have a history? The answer, it seems to us, should be obvious. Only a few men are living today who saw the beginnings of commercial electricity. Each year brings new talent to us. These new men need to know what has happened in the past as a guide to their future activities.

"Fortunately, whoever undertakes to compile such a history will find a wealth of material quickly available. Since the beginning the industry has had its journals to record the progress of the art, and early it had its associations, the proceedings of which are primary. It also has several manufacturing companies that started in the pioneer years. And finally, there are some men who go back to the beginning, or nearly so, whose memories are storehouses of early developments. And unless we act quickly, many of these minds will be stilled forever and the loss will never be recoverable."

—*Quoted from an editorial in* Electrical World, *January 27, 1940.*

Should Engineers Join a Union?

R. W. SORENSEN
FELLOW AIEE

Pointing out that engineers should have the right to join unions or not as their own consciences dictate, this author believes that by doing so they are likely to impair their claims to professional status, and suggests that they are competent to find other ways of correcting unfair situations.

ENGINEERS attain professional status in a unique way. Lawyers and physicians, upon the completion of the prescribed formal educational requirements of their respective professions, are immediately inducted into the profession by the opening of an office for practice or by joining forces with others of the profession in an established office. Engineers, upon the completion of formal educational programs (usually the work prescribed for a baccalaureate degree), get jobs as general roustabouts doing things which more often than not give no immediate evidence of a need for higher mathematics, modern physics, advanced engineering knowledge, or ability to apply engineering technique. Even at best, novitiate engineers cannot expect closer acquaintance with the real engineering problems they long to solve than that obtained by observing how engineers direct the things they are doing, or that which may be incident to training courses involving the simpler phases of manufacture and operation together with some class instruction. The latter is more often preparation for future engineering work than a study of the tasks performed in the daily training-course routine.

However humble the first jobs for graduates of engineering colleges may be, those performing the duties incident thereto soon demonstrate their qualifications or lack of qualifications for success in the practice of engineering as a profession. The reasons why this is so are clearly declared by the following statement of Gano Dunn,[1] "It is not what the engineer does, but how he does it! Not what the engineer's occupation is, but the intellectual processes by which he attacks that occupation." In other words, the engineers employed in industry do not occupy horizontal levels in the industrial scale of achievement and responsibility, but are found scattered throughout all its many departments.

Engineers in a number of occupations and localities have recently been subject to considerable pressure to unionize. This pressure has been very largely from outside organizations, rather than from the engineers themselves. Indeed such minor urge for unionization as has come from the engineers seems to be limited to those members of the great fraternity of engineering graduates who have never really become engineers, because of inability to keep up with the advancements and demands of the profession; or who have been so unfortunate as to obtain employment with firms having the shortsighted policy of getting from their technical staffs all the service possible by paying a minimum wage rather than a just compensation for the work done. This error is rare, because fortunately few industrial firms tolerate for long executives who by such practice show little knowledge of the type of management essential to continued business success. Indeed the movement to unionize engineers, set up a few months ago, at present seems to be at a very low ebb. In my opinion, this is due to the prevalence of good management, and a corresponding failure on the part of able engineers to see any reason for an engineers' union. Though the crest of the demand has subsided, aware of the fact that when there is smoke there is some fire, and urged by requests from the AIEE and the American Society of Mechanical Engineers committees on the economic status of the engineer, I am constrained to say to our younger engineers: "Look well before you leap—engineers who join unions may be committing the act which for all time classifies them as craftsmen and forever bars them from attaining the status of professional engineers."

Reasons why this is true should be quite clear to persons who analyze questions in an engineering way. James H. Herron, in a paper entitled "Unionization of Engineers"[2] says, among other things:

> "The most important union which has grown up in engineering types of employment is the Federation of Architects, Engineers, Chemists, and Technicians, affiliated with the CIO. The aims and viewpoints of this organization appear to be quite in accord with familiar labor-union purposes and ideals. According to a report of an annual meeting of the Federation which appeared in the *Architectural Forum* for November 1933, the Federation supported the following program:
>
> "1. Thirty hours of work per week.
>
> "2. Only 'extreme emergency' overtime, to be paid for at double-time rate."

Any code which prescribes such limitations is obviously designed to guard against exploitation of craftsmen and regardless of the success attained for that purpose is quite out of place for professional men doing mental rather than physical work. Such work cannot be handed on to others at shift-changing time or in many cases even be deferred until another day. Engineers, therefore, who develop habits of thinking in connection with their work as prescribed by the union code would be in grave danger of self-disqualification as professional men.

History proclaims the truth of the ancient saying: "For as a man thinketh, so is he." Men whose thoughts are directed to such objectives as a minimum of work for a maximum of pay cannot expect to experience the joy of finding an interest in their work which transcends all other interests. Without that supreme interest in a profession which makes men forget everything but the problems to be solved, and causes them to work to the limits of health and endurance forgetting time and even many of the social demands of their fellow men, there can be little probability of professional success. Professional success means that when men have finished their active years of engineering practice, they can take a backward look and say: "Those are our additions to the knowledge and the practice of our

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profession; because of what we have done men will live better than would be the case had those things been left undone."

Engineers are professional men aiming at high standards and striving to attain the same degree of recognition as that accorded the legal and medical professions. In case of severe illness, how much confidence would a patient have in a physician who after a few conferences said to him: "You will have to wait until next week for attention; I have worked all the hours I am allowed this week and can give your case no further thought at this time; or, if I do, I'll have to double my usual charge"? Perhaps the patient would need no further attention if very ill. How often would persons in need of legal aid and advice employ an attorney who said to his clients: "My allotted weekly number of work hours has been used. This is indeed unfortunate, because I have just thought of a line of argument which would be very favorable to your case if it could be studied and used for next Monday's trial, but nothing can be done about it; we must do what we can with the preparation that has been made"?

All professions include two types of work; namely, work of a research type which tends toward new developments that will enable the profession to keep pace with its rapidly and constantly changing problems; and work which can be done only by technical specialists, but is so repetitious that for the professional practitioner it becomes largely routine. The physician does his routine work in the daily treatment of his patients' minor ills; the lawyer in his preparation of the many simple agreements that are a part of the normal activities of his clients; and the engineer in his everyday tasks of building and operating standard apparatus and equipment.

No definite portion of a man's actual years in a profession which should be devoted to the training work of drafting, operating, etc., can be prescribed, but it is obvious that some stay at it overly long and become permanently subprofessional rather than professional engineers. If many have to do this simply because they are the forgotten men of the profession, such men, of course, will become discouraged and, if there seems no other way out, will think of unionization as a way to obtain coveted professional standing and increased pay.

The responsibility for this onerous situation may belong to unwise management; or to the failure of engineers to qualify properly for work more complex than their current occupations; or to a combination of unwise management and lack of forethought on the part of engineers in anticipating the requirements of the larger responsibilities that come with desired promotion.

Engineers must do their part by keeping well qualified for advancement, and management must do its part by avoiding tendencies to have advancement opportunities become departmental and by keeping working conditions and salaries for engineers at levels equitable in comparison with the work done and wages obtained by craftsmen by union methods. The question of wage is hardly pertinent to this article, but quite often one encounters, particularly in operating organizations, a deficiency in promotional programs that makes free transfer from department to department very difficult or even impossible. This situation seems to be more acute where promotion is obtained by examination (as in civil service) than it is where examinations are not used, although not all organizations using the latter scheme are free from this fault. In some instances, men have found it necessary to resign from a company and be reemployed for another department to get the consideration desired.

The question as to whether engineers shall or shall not become members of a union must be considered entirely as a personal matter for each individual, who as such has the free right to choose what seems to be the better way. This does not mean that the engineering societies have no responsibility in advising young engineers, who are the ones most affected by the decision regarding the question of unionization, but it does mean that the responsibility of these organizations should be only that of providing information and education concerning the influence of such decision, rather than making rules or prescribing whether members of the societies should or should not also be members of an engineers' union. In other words, freedom of action dictates that engineers should have the right to be union or nonunion men according to the dictates of their own consciences.

If the trend of thought in the near future indicates that engineers need more information for determining what the dictates of their consciences should be, does it not seem logical to expect that such information may be obtained effectively without the formation of any new engineering societies? Furthermore, should the results of a survey made to gather that information be such as to indicate that the engineers are not getting the recognition or compensation to which the services they render entitle them, does it not seem logical to expect that engineers are competent to find ways for having situations that seem to them unjust analyzed and corrected by peaceful methods rather than by such drastic methods as practiced by unions? One of the better methods is that used by the American Association of University Professors when a teacher reports that the college or university by which he is employed has been using unfair practice.

Indeed, engineers will delay the attainment of the high professional status so eagerly sought in direct proportion to the amount by which they deviate from the high ideals epitomized by Doctor Vannevar Bush,[3] president of the Carnegie Institution and formerly vice-president and dean of Massachusetts Institute of Technology, in his address before the meeting of the American Engineering Council in January 1939, as "the heights of true professional attainment, where honor and individual recognition by fellows is the real reward, and where the watchword is that old, old theme, which has never lost its power, and which may yet save a sorry world, simple ministration to the people."

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"This Culture"

JOHN C. PARKER
FELLOW AIEE

Deploring the "uneasy self-consciousness" that afflicts many engineers in considering "culture," Past President Parker suggests that the culture which consists of mental flexibility, sympathy with others' interests, and understanding of the relation of one's profession to society also may be instilled through great teaching of technical subjects.

INCREASINGLY, members of the engineering profession have become concerned over the state of their souls, and in increasing degree have become conscious of cultural deficiencies in the profession. This concern over the social shortcomings of the engineer is not peculiar to the teachers of engineering but indeed is pretty active in the expressions, if not in the minds, of practicing engineers quite remote from educational activities. It may benefit us to do a little bit in the way of analyzing what, if anything, we have in mind.

It's frightfully hard to discuss the cultural state of the engineer since, like many another quality, it almost vanishes by virtue of being questioned. People sensitive to the high demands of personal honor are not likely willingly to discuss their integrity. One's affections are so sensitive a thing as almost to take flight through the assertion of their existence. Our nearest approach to safety in the present discussion may lie in the cowardly refuge of discussing the profession as a whole, except for those of us who are here present.

Concern for the intellectual and spiritual background of our profession may be worthy or it may be tawdry, depending altogether on the motives actuating that concern. I feel that, to a large degree, much of the discussion among active practitioners, and teachers as well, on this particular subject of culture is of a sort which cannot accomplish its ends until by use we have got so far from the original motivation that the source has completely been forgotten. I refer to the often-expressed belief that the engineer can increase his financial take or his status in society by a self-conscious or by an administered effort to expose him to things outside the narrow range of his profession. Such a motivation is mercenary or snobbish. It is the sort of thing that makes the very name of culture a repugnant thing. It is no different from a desire to be seen with the right people, to be correctly clothed according to the prescriptions of a haberdasher's schedule, or to be proficient in the precepts of Emily Post. A desire for culture as a means of gain or of either personal or professional acceptability merits and inevitably will receive the climber's reward.

To the degree that we concern ourselves with the ability of the young engineer to live a richer and fuller life, to the extent to which we address ourselves to improving the ability of our profession to serve the society—to that degree we must give fuller consideration to things beyond the limits of our technical fitness for our jobs. With such a motivation we won't speak of "culture."

Is this too nice a differentiation? I think not. It seems to me to be about the same thing as the distinction between politeness and courtesy. The latter is "of the court", a way of life, and will, when occasion warrants, violate all the formulae for surface polish though appropriating to itself such practices of politeness as are at once the means for and the evidence of a nice consideration for the rights and feelings of others. So, granted a fundamentally sound motive and reasonable sensitiveness, I think the evidences of culture cannot be lacking. With unworthy motives only the evidences can appear and they will crack through under stress.

This culture is not a superficial adornment to be applied from without but something that must have its origin in the very soul of a people. The outward expressions must flow from what is within if we are to avoid the artificial, even the ludicrous. The barbarian may have a fine dignity and an essential nobility of character. His dignity becomes pomposity and his nobility becomes a hideous toadyism when he attempts to appropriate to himself the external stigmata of civilization. We of the western world have done something of this sort as we have viewed European civilization. Instead of admiring frankly the fine things possessed by the older world while at the same time remaining keenly conscious of our peculiar contributions to the civilization, we have on many occasions erred in one direction or the other, in both cases giving evidence of an uneasy self-consciousness. Some have deprecated all things American and given an indecent adulation to European culture. Others have been assertive of our least noble attainments—mostly the possessive ones—and contemptuous of the things developed and prized in the centuries of European growth. Still others, and perhaps the majority, have done both things simultaneously.

I believe engineers quite commonly have pursued a parallel form of snobbery. We know the rugged engineer who assertively glories in the fact that he has a redblooded contempt for poetry. We know the deprecatory type who are willing to refer to themselves and to their fellows as mere blacksmiths.

Is it perhaps from this self-consciousness that much of the discussion of culture for the engineer arises? Is it for this reason that engineering curricula seem to say, "go to, now, we're going to get culture"? Is it something of

Verbatim transcription of an address delivered at the fall meeting of the Middle Atlantic section, Society for the Promotion of Engineering Education, Brooklyn, N. Y., December 9, 1939.

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this sort which leads to the inclusion in school catalogs of a statement which might be paraphrased somewhat after this fashion: "We give 'em a real practical education, but out of the four years we chisel 10 per cent in which we make 'em take culture, damn 'em."

And what of this grudgingly conceded 10, 15, or 20 per cent of meticulously computed "culture"? French and/or German and/or Spanish, "for engineers", half apologized for, because forsooth the engineer may want to read a foreign article in the original or to do business in Latin America; but nothing under any circumstances of the great literature or of the institutions of France or Germany or of the glory that was Spain (slightly to paraphrase). English—report writing for engineers, but heaven help the poor fool of a student who would like to know something of Chaucer or of the Elizabethans. Economics because it's the fashion of the day and because the engineer must carry on his job as an adjunct to economic process, but never—so help us—a study of the archaic Adam Smith or of John Stuart Mill as a preparation for citizenship. Even psychology because the youngster can be cajoled into believing that it will offer him a facility in outsmarting the other fellow.

If this be culture, lead me to the smithshop where my soul can glow with the iron under the hammer, where its resistive co-operation can communicate its qualities through fingertips and muscles to my inner being, where through frustration and persistence I can experience the joys of attainment, but where by no stretch of the imagination will I find a misleading label of culture, and yet the elements of culture are there.

Mere workmanship never can rise to the level of a fine art, but equally it may be doubted whether great art ever has existed except as it has been grounded in sincere and loving workmanship—in a workmanship so devoted that the artisan has poured all of his aspirations and of his ideals through his peculiar medium of expression into the thing that he has created. Isn't it this fine workmanship that identifies the work of the medieval armorer, the builder of a great structurally honest cathedral, a Rodin carving a vital "hand of God" and giving warm life to cold marble, and the musicianship of a Koussevitzky? Isn't it the high intellectual integrity and love of the work that gives an inspired craftsman the same gentleness and the same nobility whether he be a millwright, a guide on a fishing stream, a sonneteer, or a statesmen?

I am sure that you all know precisely what I mean—that in your personal acquaintance you number many finely cultured gentlemen, who, through their vocations, have developed sensitiveness and strength of character without benefit of either social or scholastic background.

DANGER OF STERILITY IN ARTS COURSES

By no manner of means are all of the sins in the name of culture committed in our curricula of engineering. As I believe there is no cultural salvation merely in the "die-der-den-die" business of elementary German, so I would find cultural sterility in a Browning course made up of scholarly footnotes which may bury the throbbingly vital humanity of "The Ring and the Book" so deep in academic dust as to make Browning as obscure as he is sometimes believed to be.

Let us make sure that we differentiate scholarship from culture. Each complements the other; each is almost essential to the other; and yet they are different things. I would not for a moment deprecate sound scholarship in any field, nor would I be thought to condemn the mechanical preparation in the elements so necessary to a full attainment of the later joys. Simply I insist that courses in the liberal arts are neither liberal nor art if they fail to get beyond the mechanics of preparation or the minutiae of research. Too often this is precisely what does happen. The invasion of the scientific method into the humanities has done wonders for research but often at the expense of the liberalizing and human values in the subject matter. Too often the attractions of scholarship have resulted in slovenly and frightfully mechanical processes in the elemental preparatory courses, perhaps with the thought that scholarship is great and elemental teaching only a painful incident thereto.

If our courses in the liberal arts must be given in their initiatory phases without the joy of discovery by the student, and in their more advanced development primarily as exercises in scholasticism, I maintain that there is precious little of culture in them. Better by far would the student pursue research in the more exact mathematical and physical sciences and in their professional derivatives where the scientific method is most highly applicable; better by far would he spend his time in an intensified discovery of elemental things close to his vocational interest.

Sending our students across the campus to take courses in the rarefied atmosphere of the liberal arts is not enough. We must make sure of the treatment that will be given to the courses which they may elect and of the existence in their teachers of a nice combination of patient workmanship, fine scholarship, and high vision.

As I sense this business of culture, it's not a matter of hanging some academic trappings on the outside of a boor or of training his tongue trippingly to repeat phrases or to refer to events in history which have left him, as a man, quite unmoved. Rather it must be to develop mental flexibility, a sympathy with the viewpoint of people of divergent interest, and understanding of where one's own vocation fits into the interests of the society to which it is at the most only ancillary. If, as one reads his Chaucer, he journeys with the Canterbury pilgrims to the shrine of Thomas and on the way experiences the manysided current humanity through which, through the ages, one increasing purpose runs, he will come to understand that his engineering, his medicine, his law best serves its function in a very human world if prosecuted to meet the needs, the desires, the very human prejudices of an actual world. He will understand, being an engineer, that men are not interested in engineering accomplishment if brought through at the expense of human suffering and maladjustments, of hideousness, dirt, and noise, or as a harsh technique intruding itself into the gentler affairs of life.

"But," one may say, "this has little to do with the work

of the engineer. It may fit the doctor and the lawyer, the preacher, who deal with human beings and with human affairs. It does not touch the engineer. His work is objective and has to do with things—with structures, machines, and circuits." Is it so? I think not. Elsewhere I have tried to develop the thought that of all the professions our profession of engineering is the most social, the most human; that the engineer works not as an individual but collectively with others—researchers, designers, producers, and adapters—to direct the forces and materials of nature entirely for the service of mankind; that his profession, above all others, serves organized society and that therefore his work must be administered not only co-operatively with others but to the end of meeting the needs, the desires, the prejudices of human groups. If this be so, the engineer must, of all men, be mentally flexible, capable of adapting himself to men of different vocation with whom he must collaborate and of visualizing the social objectives of his work, its impact on the lives of others, its influence on their institutions and preferences.

The understanding of these things is not foreign to the nature of the youngsters who come to us for their schooling. They are human and as capable of mental flexibility, home background being the same, as are the young men entering the other professions. The job of the teachers of the humanities is to develop from latency into activity the mental and spiritual awareness of these students. This calls for great teaching but no greater than we ask in the technical courses. The difference is only in the media of education, and even as to these the difference is not so vast as it might seem.

CULTURAL VALUES OF GREAT TECHNICAL TEACHING

Indeed sometimes I doubt whether we are fully aware of the values that we have at hand in our scientific and technological courses for accomplishing the very purposes for which we introduce cultural requirements into our curricula. I know that the indicated courses in mathematics and physics, in chemistry, and in geology are intended primarily to equip the students with implements for the accomplishment of technical ends. I know that beyond that many of us feel that there is disciplinary value in these subjects, that the powers of observation and of close logical reasoning are developed through these pre-engineering courses. Is that all? Isn't there, beyond these more or less utilitarian values, something infinitely fine if only we can inflame the imagination of our students? Isn't there a satisfaction of the sense of sheer physical beauty in the graceful sweep of a parabola; isn't there an appeal to the sense of order and rhythm in an algebraic series?

It was my good fortune as an undergraduate to take courses in structural analysis with a great teacher whom I recall as the inventor of the method of area moments for the graphical analysis of trusses and arches. The man loved his subject. Some of that affection communicated itself in his teaching. It is true it was a course in civil engineering. Equally truly, it was a course in which we learned something of a universe of law and order, in which we gained confidence that there were no closed mysteries that could not be solved by a modest but persistent mind. It meant something to us that the great arches which some day will support the central tower of the Cathedral of Saint John the Divine have their very being in a different but equal beauty in the method of area moments. A course in geology given to us as vocational foundation was so divinely inspired that the mountains, the hills, and the streams will always add beauty to the landscape because they are full of meaning in a structural sense.

These men had no thought of departmentalizing culture. I doubt much whether they were ever quite conscious of it as an adjunct to engineering education. This I know—because they had wide intellectual horizons, because they had great love for their subjects, because they were aware of the gorgeous intangibles in the things they taught, they communicated some faint bit of their wideness of vision to us young unregenerates. No man could take a magnificently interpretative course in the theory of dynamics of the rigid body with a professor who was a distinguished linguist, a skilled amateur of the violin, an historian and an economist, and with all a very fancy figure skater, and at the same time have either contempt for the niceties of mind and soul in other men or deprecation of the elements of those qualities in his own profession.

Teachers such as these work greatly on the young men who sit under them. Both in themselves and in their approach to the technical subject matter of their courses they carry the cultural essentials. They have a reverence for learning for its own sake and a respect for it no whit abated by the fact that it may be put to work. They speak the King's English with appreciation of it not only as a wonderful medium for the communication of ideas but as a source of enjoyment in and of itself. Their hours of leisure may find them occasionally listening to good chamber music, reading modern or classical writings not for the subject matter alone but for sheer enjoyment of the writer, participating in the affairs of men because they know that people are greater than their creations. Such teachers ungrudgingly see their students, in the spirit of true amateurism, making excursions into unvocational fields. Equally they resent any implication that their own work can be less than scholarly, least of all narrowly vocational.

Without such teaching in the technical courses all the cultural courses in the curriculum are without effect. Lacking this everyday domestic point of view, they are as pointless as Sunday piety among the irreligious or as the sending of a youngster from a vulgar home into an importuned contact with a narrowly modish group.

What I have been trying to say comes down pretty closely to this: that the finer culture of the minds and souls of our young engineers will lie in the fitting of them to enjoy their jobs and their lives outside their hours of work and in helping them to learn sympathetically to view the interests and the vocations of other men; that this can be done through helping them to find the less obvious qualities in various matters coming within the range of human interests; and that this culture is to be had only through great teaching, whether it be in our professional courses or across the yard.

Room Noise at Telephone Locations—II

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ASSOCIATE AIEE

Surveys of room noise at various locations under both summer and winter conditions provide data for annual averages and distributions of room noise, and indicate the relative importance of major noise sources

As PART of a study of room noise and its effects on telephone transmission, a broad survey of room-noise conditions at telephone locations has been made by Bell System engineers which has provided information relating to the magnitude of room noise at various types of locations and its variation from place to place and from time to time.

Room-noise data, based primarily on measurements made at about 900 locations in and around Philadelphia and Chicago under winter conditions, were reported informally to the conference on sound at the 1939 AIEE winter convention (see footnote). The present article supplements the earlier material and includes a summary of room-noise conditions expressed in terms of annual averages based on both the winter survey data previously discussed and the summer survey data that had been obtained at about 1,300 locations but had not been completely analyzed at the time of the earlier report. The summer survey included 500 measurements at locations previously measured during the winter in and around Philadelphia and Chicago, and 800 measurements at locations in and around Cleveland, New York City, northern New Jersey, and Philadelphia. Annual average as used in this article is the mean of winter and summer measurements. In addition, the present article includes a brief discussion of outdoor noise and the relative frequency of occurrence of several predominant sources of room noise.

The noise measurements were made with equipment conforming to the specifications described in the ASA "Tentative Standards for Sound Level Meters" (Z24.3-1936), using the 40-decibel loudness-weighting network. The measurements are expressed in terms of sound level in decibels above reference sound level, that is, 10^{-16} watt per square centimeter at 1,000 cycles in a free progressive wave, each measurement being based on the average of 50 individual readings.

Since room noise is a highly variable quantity it is desirable to express the results of room-noise measurements in such a way that both the average value and the degree of variation involved are described. For a particular type of location, for example, the average value is obtained from the total of the measurements at all locations of this type. The degree of variation involved is expressed in terms of the standard deviation, this term being a measure of the spread of the measurements. The results may also be expressed graphically by means of distribution curves showing the cumulative per cent of locations having noise values of a given amount or less. The distribution curves included in this paper have been prepared using an arithmetic probability scale, so that cumulative normal distributions appear as straight lines.

In order to give a condensed summary of the room-noise data obtained at various types of telephone locations, generalized distribution curves covering room noise on an annual average basis are shown on figure 1 for the three broad classifications: residence, business, and factory. The data for residence locations are shown in two parts, covering conditions with and without radios in operation, respectively. It will be noted that the measurements in residences where radios contributed to the general noise level indicated room-noise values approximately halfway be-

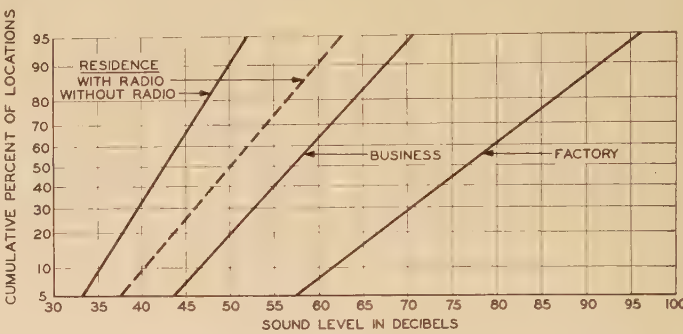

Figure 1. Distributions of room noise based on annual average levels

Summary of Annual Average Values of Room Noise and Differences Between Summer and Winter Conditions

Type of Location	Annual Average Values of Room Noise (Decibels): Average	Standard Deviation	Summer Versus Winter (Decibels)
Residence			
without radio	43	5.5	3
with radio	50	8.0	4
Small store (< 6 clerks)	53.5	7.5	4
Large store (> 5 clerks)	61	6.0	0
Small office (< 3 desks)	53.5	6.5	4.5
Medium office (3 to 10 desks)	58	6.5	1
Large office (> 10 desks)	64.5	4.5	0
Factory office	61.5	9.5	−2
Miscellaneous business	56	7.5	1.5
Factory	77	12.0	−2

Based upon a report made at the conference on sound at the AIEE winter convention, January 22–26, 1940. An earlier report on the same survey was presented at the 1939 winter convention and published in the June 1939 issue of ELECTRICAL ENGINEERING, pages 255–7.

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tween those obtained at residences without radios in operation and those obtained at business locations. Also, the average room noise at factory locations is about 20 decibels greater than at business locations. These distribution curves illustrate the fact that room noise is a highly variable quantity and cannot be described adequately in terms of average values alone.

The data shown on figure 1 are also summarized in the accompanying table in terms of annual averages and standard deviations, giving the data for business locations in somewhat greater detail to show the noise conditions at various types of such locations. In addition, the table shows the average difference between summer and winter room noise at the various types of locations, based on comparisons made at about 500 locations under both summer and winter conditions.

Considering first the average difference between summer and winter levels of room noise, it will be noted that the largest differences occur in the case of residences and small stores and offices. This appears reasonable since it would be expected that the increment of noise from outdoor sources entering through open windows or doors under warm weather conditions would have a greater effect in these types of locations than in the larger establishments where the noise due to indoor sources (people and store or office appliances) is of greater importance. In the case of factories and factory offices the decrease of 2 decibels under summer as compared to winter conditions is due presumably to differences in the rate of manufacturing activity in the two seasons.

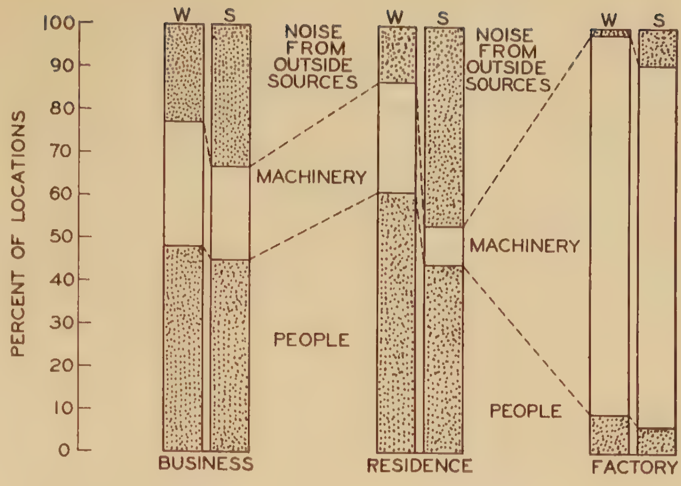

Figure 4. Distribution of locations by predominant sources of noise

The average levels shown in the table are based on measurements made in a wide variety of types of areas ranging from quiet rural regions to noisy city districts. The standard deviations shown thus include the effects of variations in the levels of room noise that occur from one type of area to another, as well as the variation between locations in a single area. In terms of annual average values, the room-noise data cover a range from about 43 decibels for residential locations without radios in operation to 77 decibels for factories, with the various types of business locations covering an intermediate range from 53.5 to 64.5 decibels. The standard deviations involved are of the order of 5.5 decibels for residential locations, 4.5 to 9.5 decibels for business locations, and 12 decibels for factories.

Since in many instances outdoor noise is an important contributor to room noise, measurements were made of outdoor noise at the street curb in front of the premises in which room-noise measurements had been made. The results of these measurements are shown by the three sets of distributions in figure 2, which are based on data obtained (1) under summer conditions in New York City, (2) under summer conditions in locations other than New York City, and (3) under winter conditions in locations other than New York City. Each set includes separate distributions for business and for residence locations.

Figure 2 shows that the average outdoor noise (for both business and residence locations) in New York City is of the order of 10 decibels greater than in the other areas. Also, the spread of the noise conditions in New York City is somewhat smaller, in view of the more uniform type of area, than that for conditions in the other groups of locations, which include a range from congested city districts to rural areas. Since measurements in congested districts in Chicago and Philadelphia gave values of the same magnitude as those obtained in New York, and since the distributions shown in figure 2 tend to approach a common

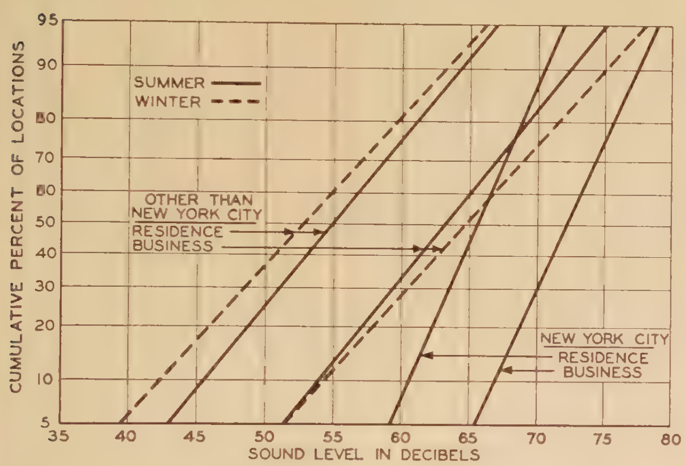

Figure 2. Distributions of outdoor noise under summer and winter conditions

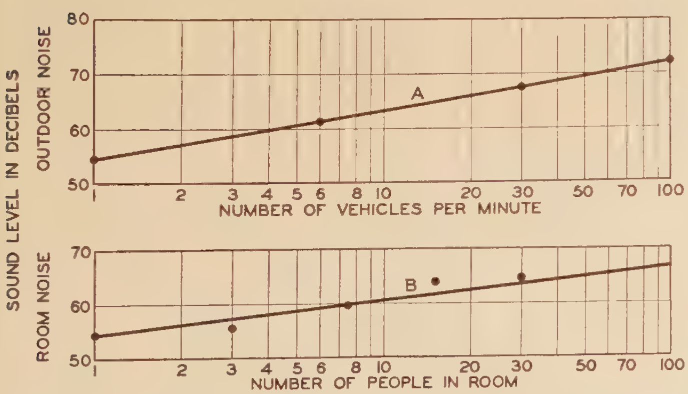

Figure 3. Relations between (A) outdoor noise and vehicular traffic, and (B) room noise at business locations and number of people in room

maximum value, it seems probable that the distributions obtained for New York City are also representative of noise conditions in the congested districts of other large cities.

Figure 3 shows the relation between outdoor noise and the volume of street traffic in terms of vehicles per minute and also the relation between room noise at business locations and the number of people in the room. The outdoor noise appears to be directly related to the logarithm of the number of vehicles per minute. It is of interest that the relation between outdoor noise and vehicular traffic found at this time is in very good agreement with the relation found in New York City in 1930, as shown in the Noise Abatement Commission's report on "City Noise." As shown in the lower portion of figure 3, the room noise at business locations tends to increase with the logarithm of the number of people in the room. In this case the results are somewhat more erratic and the slope of the logarithmic curve is somewhat less than that of the curve for the relation of outdoor noise to vehicle traffic. These differences are of the type which would be expected from a consideration of the sources of outdoor noise and room noise. Outdoors, vehicular traffic constitutes, in general, the major noise source; indoors, noise from outside sources and from machinery, which together form a substantial part of room noise, tend to reduce the effect of variations caused by people. Also, rooms containing larger numbers of people are usually larger in size, which tends to offset the increment of noise caused by the additional people.

In the measurement of room noise at each location, the source of noise judged to be predominant was noted on the data sheets. It should be appreciated that the level of room noise at a particular location is varying continuously. At each location measured each of the 50 individual readings of the sound-level meter was classified by the observer on a judgment basis as to the probable source that affected the reading. The location was then classified as to source of noise in accordance with the majority of the individual reading classifications. The results of an analysis of this information are shown on figure 4, with the sources grouped into three general classes: people, machinery, outdoor sources. Data are shown for winter and summer conditions separately for each of three general classifications of locations, business, residence, and factory. The winter and summer data are based on the results of the complete winter and summer surveys, respectively. Accordingly, although in each case the results are believed to be reasonably representative, the relations between summer and winter should not be considered quantitatively, since the locations involved are not identical for the two cases. It is interesting to note the relatively large proportion of both business and residential locations at which the predominant source of noise is people talking or moving about. It may also be noted that there is a marked decrease from summer to winter in the proportion of both business and residence locations at which noise from outdoor sources predominates.

Power Supply for Suburban Areas

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The practices of a large operating company in providing power supply for a load of approximately 150,000 kva in a 1,400-square-mile suburban area are discussed in this article, with the underlying causes—practical, economic, and electrical—for these practices.

SOME years ago the load density of the strictly suburban area of the Philadelphia Electric Company was such that a fairly large percentage of the load was adequately supplied from 13-kv lines, but growth of load has made it economically desirable gradually to reinsulate a large proportion of these for 33-kv operation. By such change-over capacity was provided at lower costs than by any other means. Aside from reinsulating existing lines for higher-voltage operation, capacity has been provided by increasing the number of supply lines and by erecting 66—33-kv stepdown substations at new locations. In suburban areas, it is expected that load growth for many years will be provided for largely by the erection of new 66-kv stepdown substations in addition to the five now in use. Scarcity of low-cost routes for 33-kv circuits, service reliability, and increased load densities are factors of importance in determining this policy. Previous use of 66-kv in Philadelphia determined its selection as a voltage for suburban areas.

A principle that has been generally followed in recent years is that of installing but one transformer bank at each 66—33 kv substation, provided that in the event of its failure, the capacity of 33-kv lines to adjacent 66—33-kv substations is sufficient to carry the load with not too great a drop in voltage. While three of the five 66—33-kv substations have two banks, this is due to historical or other reasons, and is not a negation of the general principle.

In considering the problem of reliability of supply lines, it is helpful, as a guide for the intelligent expenditure of

Essential substance of AIEE paper 39-172, presented at the Middle Eastern District meeting, Scranton, Pa., October 11–13, 1939.

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money, to know approximately the causes for interruptions. Table I presents some data on causes of supply-line tripping in the suburban area.

It can readily be seen that if increased supply-line reliability is desired, the greatest emphasis should be on the elimination of outages caused by lightning, as such interruptions represent on the order of three-quarters of the total. Attention has been concentrated on this problem for some years in the past, with the result that lightning troubles on newly designed lines are approximately half of those previously experienced.

On all new 33-kv supply lines, as well as when complete rebuilding is undertaken, the aim is to secure a minimum spacing of two inches per kilovolt between conductors and between conductors and ground, as measured by way of the insulators, wood crossarms, and wood pole, except that on the insulators the arc-over distance rather than the distance measured over the surface corrugations is used in the measurement. In practice, at least 2.5 inches is usually secured. Experience indicates that substantial improvement is secured up to this spacing, but that little improvement results when it is exceeded. Aside from rebuilding lines to secure a minimum of two inches per kilovolt, a great deal of other work, such as lowering guys, has been done to increase spacing. Although such work does not always bring spacing up to the desired minimum, it does cause marked improvement in reliability.

In considering the need for expenditures to improve supply lines, it is desirable to know what proportion of the outages to the electricity supply system are due to supply-line troubles. Collection of such data may be laborious and costly, but the results should be of value as a guide for the expenditure of money. Table II presents some statistical data on the distribution of such outages in the Philadelphia Electric Company suburban area.

The need for stressing improved supply-line performance particularly for single-line substations, can readily be seen from this tabulation. Many lines serve both single and multiline substations. Customers supplied from single-line substations experienced about three times the outage minutes of those supplied from multiline substations.

SUBSTATIONS

General practice for extremely light load-density areas calls for the use of single-bank single-line substations, largely because two-bank two-line substations would not be economically feasible. For such areas there is used either a pole-mounted substation (figure 1), or a recently developed factory-assembled self-contained 1,000-kva unit substation, shown in figure 2, which requires the minimum of work in installation and connection to supply lines and distribution circuits. The major advantages of the factory-assembled unit lie in its better appearance, and in the fact that very little investment has to be written off if it becomes necessary or desirable to move it to another location. Such unit substations on the Philadelphia Electric Company system are equipped with an air circuit breaker and tap-changing-under-load equipment with a 15 per cent range in eight steps on the low-voltage side, and suitable relays and load-recording equipment. Either external fuses or fusible links under the oil are provided on the high-voltage side.

For heavier load densities, multibank multiline substations are usually provided. On the Philadelphia Electric Company system, the most common type is the so-called loop substation which contains two transformer banks, each with a low-voltage automatic breaker and served on the high-voltage side by two 33-kv lines looped through a 33-kv breaker as indicated in the simplified single-line diagram of figure 3 and illustrated in figure 4. In case of fault on one of the 33-kv lines, the 33-kv breaker and the low-voltage breaker on the bank nearest the fault open automatically. The auxiliary bus is provided so that even with failure of substation equipment on an individual circuit, the load of the circuit can be carried without recourse to street breakdowns, although hand switching is necessary to put the equipment on the auxiliary bus. In one recent case of modernization of a substation, the auxiliary bus has been omitted. In its place, an emergency circuit supplied directly from one of the two transformer banks has been extended to the point on each circuit where the underground cable terminates and the aerial wire portion begins. By closure of a disconnecting device at this point, any circuit can be carried in an emergency. A still larger substation, shown in figure 5, is used where near-urban load densities are encountered. Table III gives the average number of interruptions per year, based on a five-year record, of substations of various sizes, and illustrates the increased reliability provided for the heavier loads.

The interruptions to the smallest substations are about nine times as frequent as those for the largest substations.

As indicated in table II, the reliability of the single-

Table I. Causes of Interruptions to Suburban 33-Kv Supply Lines of Philadelphia Electric Company

Cause	Per Cent of Total
Line insulator flashover—lightning	55
Pole switch flashover—lightning	8
Wires down due to lightning	13
Wires down not due to lightning	5
Trees and foreign objects	8
All other causes	11
Total	100

Table II. Durations of 115/230 Volt Suburban Customer Outages, Expressed in Per Cent

Cause of Outage	Single-Line Substations	Multiline Substations
Source	4	4
Supply line	50	5
Substation	12	1
Distribution primaries	28	78
Distribution transformers	2	5
Miscellaneous	4	7
Totals	100	100

Table III. Average Number of Total Interruptions to Suburban Substations Per Year

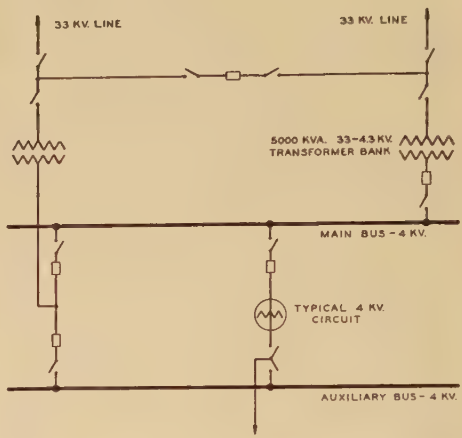
(Average of Last Five Years)

Kva Load Per Substation	Number of Interruptions Per Substation	Number of Substations
5,000 or over	1.1	8
3,000 to 4,999	1.3	7
1,000 to 2,999	2.7	11
500 to 999	7.7	13
100 to 499	9.6	25

Figure 1 (left). Small pole-mounted substation

Figure 2 (left). Factory assembled, self-contained 1,000-kva unit substation

Figure 3 (below). Simplified single-line diagram of a 33-kv suburban loop substation



bank suburban substation service is as dependent on the reliability of its supply lines as on any other combination of factors. Approximately 50 per cent of the outage minutes in single-line substations and 5 per cent in multi-line substations are due to supply-line outages.

The major source of trouble within the substation itself is in the failure of oil circuit breakers. The fire which frequently follows breaker failure is particularly serious because of the headway it gains before it is known, as most suburban substations are unattended. The damage from the fire delays materially the return of the substation to service. Use of oilless breakers may prove to be the solution to this problem; various types of these breakers have been in active operation for several years.

Figure 4. Typical suburban 33-kv substation with building developed for one-half its ultimate capacity

Introduction of additional 66—33-kv substations will automatically provide for a radical improvement in the reliability of substation service by cutting the length of line exposure. On single-bank single-line substations, supply-line reliability should improve approximately inversely to line length. With lines of similar characteristics and equal chances of having interruptions on a per-mile basis, the relative probability of simultaneous outage to a two-line substation with its existing and proposed shortened lines, is proportional to the product of the length of the lines that supply it. Hence, if each of the two lines to a particular substation is cut in half, the probability of outage due to line trouble is cut to one-fourth. Such improvement is another factor which should be given considerable weight in determining whether capacity is to be provided by extending medium-voltage supply lines, or by additional high-voltage lines with their associated 66—33-kv substations.

PRIMARY DISTRIBUTION

The nominal distribution voltage most frequently used throughout the United States today ranges from 4,000 to 4,800 volts three phase. The adoption of such a more or less standardized voltage probably is due in part to the fact that the voltages that preceded it were either 2,300 volts three phase delta or 2,300 volts two phase. Change-over from either of these two systems was relatively easy because the phase-to-neutral voltage at 4 kv, for example, is the same as the phase-to-phase voltage on the 2,300-volt three-phase delta system and the phase-to-neutral voltage on the two-phase system. In any event these factors accounted for the use of a nominal 4-kv system in the suburban area around Philadelphia. For the lightest load-density areas, a higher voltage than 4 kv might locally show greater economies, but considering over-all long-time requirements, standardization at 4 kv is believed to represent the best solution.

One of the difficulties in the adoption of a 4-kv three-phase system over a 2.4-kv two-phase system lies in designing a satisfactory three-phase four-wire secondary system for combined light and power loads. With the two-phase system a five-wire four-phase secondary was used which provided 115 volts for lamps and 230 volts for motors. With three-phase, four-wire, wye secondaries, the three-phase motor voltage would be about 190 volts on a 110-volt system instead of 220, the standard motor

rating, which may make it necessary to use larger motors or autotransformers for motor supply. Proper solution of this problem lies in the design of a 190-volt motor for use on such combined light and power secondaries. This matter is being seriously considered by the industry at the present time and there appears to be no serious obstacle to the adoption of such a standard motor.

The problem of securing the maximum results from automatic voltage-regulating equipment on primary distribution circuits is greatly accentuated in suburban areas because of the greater length of the circuits. Among the distribution circuits from a particular substation, the probabilities are that there are some which will be heavily loaded when the substation load is at its maximum and on which the nearest customer will be at a considerable distance from the substation, and at least one which either will be very lightly loaded or will have customers immediately adjacent to the substation. The voltage drop on the longest circuit frequently makes it desirable to have the bus voltage at as high a value as possible so long as the regulators on the lightly loaded circuits or on circuits with near-by customers have sufficient bucking range not to give these customers too high voltage. Only by such a procedure is it possible to make use of the entire 20 per cent range of the plus-or-minus 10 per cent regulators commonly used. Failure to operate the system in such a manner may easily force the introduction of new circuits before the existing circuits are fully loaded, the use of costly auxiliary regulating devices out on the street itself, or the use of larger copper conductors in the street to reduce voltage drop.

In extreme emergencies, it is the practice of the Philadelphia Electric Company to permit the customer's infrequency of occurrence, it is to the best interest of customers to permit the voltage to sag. The minimum permissible emergency voltage designed for at the customer's meter is 95, because tests on a group of new refrigerator motors indicated that all makes of motors tested will start when 95 volts is supplied but that certain motors will not start at 90 volts. At the present time, delivery of emergency voltages for 220-volt polyphase motors has not been much of a problem because combined light and power secondaries have been used to only a limited extent, but if their use becomes desirable on a large scale because of a new type of load, such as a residential five-horsepower air-conditioning motor load, inability to start such motors at 165 volts, which corresponds approximately to 95 volts single phase, may force the use of higher emergency voltages and result in a substantial increase in system investment.

An auxiliary advantage in operating with a high bus voltage, even though it normally may not be required for all or any of the circuits in the substation and even though it is so high that circuits never normally operate in any but the bucking range of the regulator, lies in the fact that it is possible to give customers more nearly normal voltages in emergencies than would otherwise be the case, or even to postpone the installation of an additional supply line. In suburban areas with long supply lines, voltage drop in the line, both normally and in emergencies, frequently requires the installation of additional lines, even though there is ample thermal capacity in the available equipment. Loss of one of the supply lines which serve a multiline substation accentuates the voltage difficulties and the voltage level at the substation bus may be reduced by substantial percentages. Regula-

Figure 5. Type of substation used for near-urban load densities

voltage to sag below normal limits. Actually, there are three choices available for handling such emergency conditions: selected loads may be dropped, giving no voltage to some customers; voltage may be allowed to sag; or large sums of money may be spent in an attempt to give normal voltage to all customers. Because of the tion of bus voltage at 66—33-kv substations, by providing the highest voltage at the heaviest load period, can be helpful in substantially increasing the capacity of supply lines. This practice is used where voltage-regulating devices are available, subject to the limitations of near-by loads. In urban areas, normal and emergency bus volt-

ages are not generally a problem because cable supply lines are usually necessary, and aerial lines, if any, are short.

In recent years, increased attention has been given to the possibilities of distribution primary networks. Such networks greatly reduce the probability of outage to customers served from substations supplied by single lines, mainly because service is not interrupted when one line is lost. Of course, some improvement is also secured by reduction in outages due to primary distribution system troubles. Better normal and emergency voltage regulation and reduced voltage flicker are incidental advantages. Few of the single-phase branches and only certain of the main polyphase portions are actually tied together to form the network loops, and these probably represent substantially less than 50 per cent of the total circuit mileage. Complete network distribution at present load densities would involve costs out of line with the added gain.

New High-Voltage Laboratory of the Bureau of Standards

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MEMBER AIEE

More effective service to the Federal Government and the electrical industry, and broader co-operation with national technical societies are anticipated as the National Bureau of Standards takes over its new specially designed laboratory for high-voltage and X-ray work.

On April 6, 1940, there was turned over to the National Bureau of Standards by the contractor the new $350,000 laboratory building that is to be devoted to high-voltage and X-ray work. This event marks a definite step in the growth of the Bureau and in its possibilities of service to the public and to industry. The work to be carried on in the new laboratory will be an extension of that done on a necessarily more limited scale in the cramped quarters hitherto available.

The work of the laboratory falls naturally into four classes: X-ray and nuclear physics studies, the precise calibration of voltage transformers, testing of insulating materials for the Federal Government, and research and development on methods of measurement at high voltages.

The new laboratory is an unusual building in many respects. It was designed by the office of the supervising architect, Public Buildings Administration, Federal Works Agency. Because of the special requirements to be met, the closest co-operation was essential between the architects and the laboratory workers. The bulk of the building consists of a single huge room 136 feet long, 65 feet wide, and 60 feet high, in which the equipment for the higher voltages will be housed. In front of this is a series of smaller laboratories, occupying five stories, in which apparatus for somewhat lower voltage will be installed and which will also contain office space and control apparatus for the higher-voltage equipments. The walls of the large room are lined with a layer of sheet copper and the exterior walls are thermally insulated with a three-inch layer of cork. The ceiling is metal, and steel armor has been cast in the concrete floor and bonded to the steel frame of the building. The metallic conducting lining serves three purposes. It makes the bound charges induced on the walls by the presence of electrically charged conductors definite and repeatable. It prevents interference with radio measurements in other laboratories, and it also makes the walls relatively tight against infiltration of water vapor. The climate of Washington in summer is so humid that many types of electrical measurements become impossible by reason of the leakage of electricity over the surface of insulating parts. Special equipment is provided in the new laboratory so that the air in the interior of the building can be dried.

Three openings are provided high in the north wall of the large room. The central opening is 16 feet square and the side openings are 10 feet square. The openings are normally closed but will permit a three-phase 600,000-volt or a single-phase 1,000,000-volt circuit to be run outside the laboratory for experimental purposes.

To protect the workers in the small laboratories at the front of the building from scattered X radiation, a heavy (12-inch) concrete wall separates them from the main room. Also, the targets of the high-voltage X-ray tubes are located within a 12-inch concrete "pill box" on the main floor. Lead-covered doors and concrete labyrinth passages separate the X-ray laboratories from the other half of the building.

In order to isolate all equipment which might produce noise or vibration in the main building, a small annex has been built, north of the main laboratory. This will house storage batteries, transformers, motor-generator sets, and compressors. Three experimental generators having ratings of 5 kva, 50 kva, and 1,500 kva, respectively, are provided. Each of these can be driven by a 60-cycle synchronous motor but alternatively can be driven by a d-c shunt motor when frequencies other than 60 cycles per second are needed.

The equipment for X-ray work includes a cascaded bank

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Plan of main floor of laboratory

1. Air ducts
2. Pit for oil tank
3. Brooks electrometer

3A-3B. Standard transformers, 25 kv

4. Impulse generator, 2,000 kv
5. Dark room
6. Distribution switchboard
7. Elevator
8. Hatchways to basement
9. Cathode-ray oscillograph
10. Air capacitor

10A-10B. Standard transformers, 100 kv

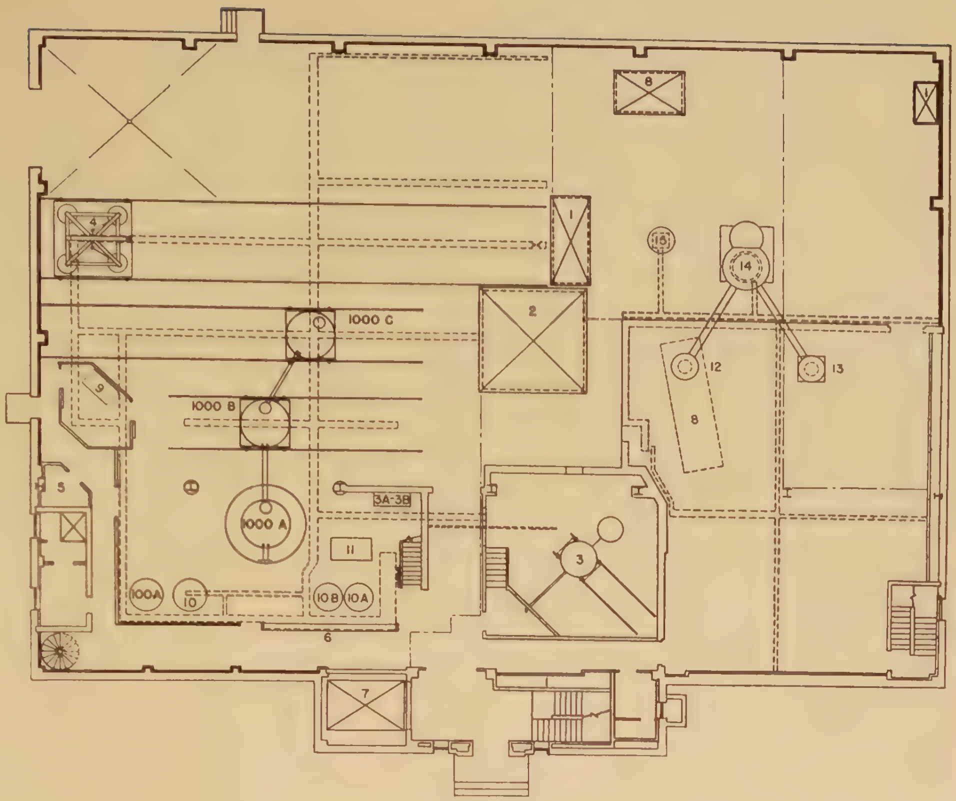
11. Shielded resistor, 500,000 ohms, 30 kv

12–13. X-ray tubes

14. D-c generator, 1,400 kv
15. Ion tube

100A. Standard transformer, 250 kv

1000A-B-C. Cascade transformers, 350 kv each



of ten units, each consisting of a transformer, rectifier, and capacitor connected in series to produce 1,400,000 volts direct current of either polarity with a current rating of 25 milliamperes. This can be used to supply any one of three vacuum tubes, two of which are for X rays, while the third is a source of neutrons. Smaller equipments giving 400,000 volts, 200,000 volts, and 10,000 volts will be moved into the smaller laboratories from their present location at the Bureau. Within the last few years the developments of manufacturers of X-ray apparatus have made possible the use in hospitals and laboratories of 1,000,000-volt X rays. Because of their greater penetrating power, such rays may have great utility in the therapeutic treatment of cancer and also in the examination of large metal parts for hidden flaws and cracks. This advance has reintroduced the hazard of accidental "burning" of the operator which caused so many casualties among pioneer workers in the X-ray field, and it is therefore of vital importance that the amount of protection afforded by various types of protective equipment be known quantitatively. Another and perhaps even more important group of problems in the X-ray field is concerned with the measurement of dosage. It is essential to the progress of medical science that results obtained in one hospital should be available to workers in other hospitals in definite and quantitative terms so that results obtained on different patients can be compared. This is best accomplished by the standardization of dosage meters at some one central laboratory. As the new laboratory is located within a few miles of the National Cancer Institute and of the new Navy Medical Center, it offers possibilities for a very desirable close co-operation between the medical workers in these institutions and the physicists at the National Bureau of Standards.

The equipment for use in testing voltage transformers for ratio and phase angle is based primarily on the precision shielded resistor now used at the Bureau. This is suitable for measurements up to 30,000 volts. Two 10-kva transformers rated at 100,000 volts have been used in the past to step up the precision measurements over a range of 4:1 by changes in their high-voltage connections from parallel to series. In the new laboratory a further 2:1 step-up is obtained by an additional 100-kva transformer having two high-voltage coils which may be connected in series to give a rating of 250,000 volts.

The high-voltage attracted-disk electrometer will be installed in an interior room the temperature of which can be carefully controlled. This instrument has already been used up to 100,000 volts as an independent check on the ratio measurement, and in its new quarters will be capable of use up to 300,000 volts.

An additional independent means for measuring ratio and phase angle in the upper voltage range will be secured by the use of air capacitors.

It is planned to construct a number of such capacitors in the near future. The first of these is to be of the compressed-gas type for use up to 150,000 volts, and later a free-air capacitor is planned for 250,000 volts. These capacitors will provide an additional independent means for measuring ratio and phase angle for voltage transformers, and also can be used as standards for the measurement of dielectric loss in insulation.

For testing the dielectric strength of insulating materials and the flashover voltages of insulating structures, there will be available, in addition to the 60,000-volt transformer now in use by the Bureau, three new testing transformers of 350,000-volt rating each. These transformers can be

used individually in a three-phase star connection with 600,000 volts between lines or connected in cascade to give 1,050,000 volts to ground at 60 cycles. Because of the fact that breakdown and voltage-proof tests of insulating materials and structures require only moderate precision and can be done at many commercial laboratories, the Bureau limits its testing of this nature to material purchased by various branches of the Federal Government.

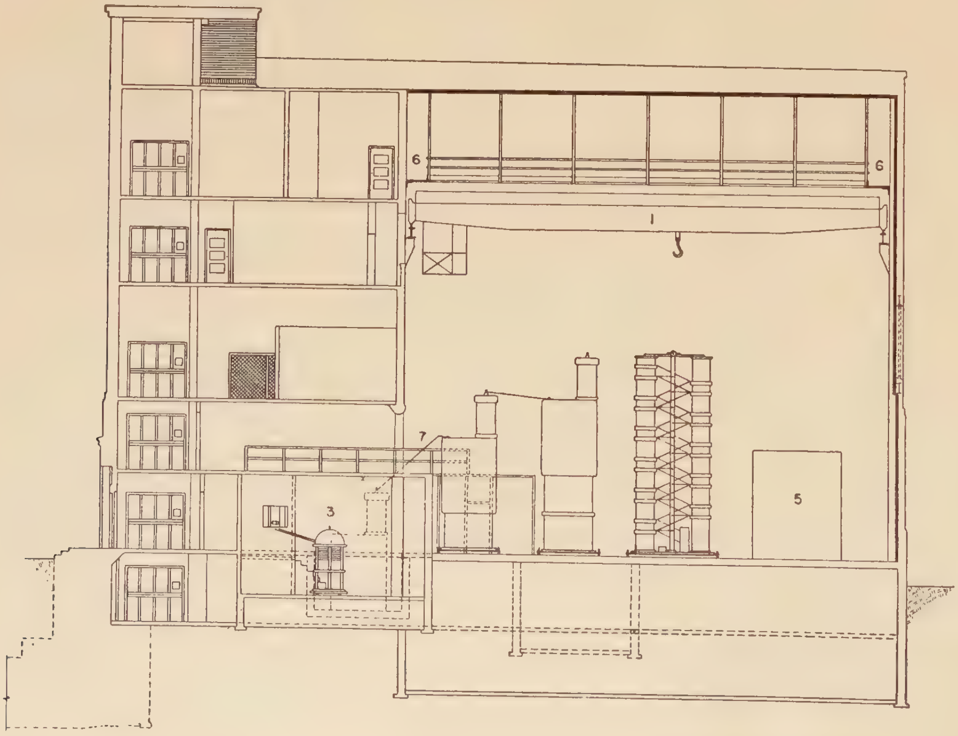
An impulse generator will also be installed in the new building. It has an energy rating of 33,000 joules, and when used with the Marx circuit a rating of 2,000,000 volts. This equipment will be so arranged that it also can be used as a source of surge currents at its charging voltage of 100,000 volts. The impulse generator and two of the cascade transformers will be mounted on trucks, so that when not in use they can be moved back against the wall, leaving more clearance for the other apparatus which is in use. A cathode-ray oscillograph of the cold-cathode type having a high writing speed will be installed for use with this impulse generator.

Extension of the scope of service of the new laboratory will be made gradually, partly because some of the equipment will not be ready for delivery before December 1940, but more especially because the available staff is limited, and because the work will lead into new and unfamiliar fields. Each step in the measurements must be based on previously tested methods and apparatus.

It is expected that the first step will be to push the precise measurement of transformer ratio up to present operating voltages of 230,000, using the electrometer, and perhaps later to check this by using an air capacitor. This probably will be followed by a study of methods for the determination of the crest voltage of sustained alternating currents, using as a standard an electrostatic method that has already been tried out on a small scale and seems capable of an accuracy approaching 0.1 per cent. This method, by reason of the small charging currents required, can then be applied in the higher voltage range to calibrate other types of crest voltmeters, including the cathode-ray oscillograph, and to determine the effective ratio of potential dividers of both the capacitance and resistance types, under a variety of conditions.

The Bureau has been active for many years in the measurement of dielectric loss in the lower-voltage range. In the new laboratory this work is expected to be extended into the range of higher voltages by using the air capacitors mentioned. A second cathode-ray oscillograph of the hot cathode type, having a sensitivity as great as three millimeters per volt, has been developed at the Bureau for the study of dielectric loss in small samples of insulating material. It is hoped that this instrument can be further developed in the new laboratory. A flexible electron optical bench has been built so that various types of electron lenses can be tried with a view toward securing the optimum conditions of focusing the electron beam. This equipment also is expected to be available for the study of focusing problems encountered in the high-voltage cold-cathode oscillograph and in X-ray tubes.

The new laboratory will enable the National Bureau of Standards to give better service both to the Federal Government and to the electrical industry, and through these agencies to the public, along the same general lines that it has given in the past. The direct service to the Government will consist to some extent of carrying out acceptance tests on insulating materials and structures purchased by the Government, but to a greater extent of special testing in connection with the development of new apparatus and the solution of unusual problems. The service to industry similarly will consist in part of the precise testing of voltage transformers and, in the future, of standards for the measurement of dielectric loss in the high-voltage range. This testing work is done for utility companies, manufacturers, and the laboratories of public-utility commissions. To an even greater extent than in the past, the service to industry is expected to include an active part in co-operative research on methods of measurement in the high-voltage range, in co-operation with technical committees of such national organizations as the American Society for Testing Materials, American Standards Association, and the AIEE.



Transverse cross-section of laboratory, looking west

1. Electric crane, 10 tons
3. Brooks electrometer
5. Shipping entrance
6. Walkway around walls
7. Control platform

Analysis of World's Fairs' Hearing Tests

ONE of the popular Bell System attractions at the World's Fairs is the hearing test. A considerable percentage of the visitors to the Bell System exhibits at both the New York Fair and the Golden Gate Exposition at San Francisco have taken advantage of the opportunity to find out how well they hear and have thus made available some three-quarters of a million records.

The tests are given in soundproof rooms, and both the tests and the instructions are given through telephone receivers. Two types of tests are given, with separate booths for each. In one, the visitor hears spoken words, which are two numbers such as "eight-six," each successive pair being at a lower volume.

In the other type of test, the two numbers are replaced by pure musical tones, each tone being sounded from one to three times, and the listeners write down the number of times they hear the tone. Five tests, each consisting of nine sets of tones at successively lower volumes, are given. The first is at a moderately low pitch, 440 cycles per second; the following tests are at 880, 1,760, 3,520, and 7,040 cycles.

Only the tone tests are recorded. The word tests give only a check on one's ability to understand spoken words, while the tone test, by providing data at five frequencies over the most important part of the aural range, is more suitable for study and analysis.

The results of this survey, in harmony with previous data, indicate a definite falling off in hearing acuity with age. This is particularly noticeable at the higher frequencies. A rather remarkable fact is that at the low frequencies, the falling off with age is less for men than for women, while at the higher frequencies it is less for women than for men. These facts are indicated in figure 1 on which average hearing loss is plotted against age for two frequencies.

This difference between men and women is brought out better in figure 2, on which the hearing loss is plotted against frequency for two age groups. In the lowest age group the difference between men and women is small, but even here the advantage is slightly with the men at low frequencies and with the women at high frequencies. In the age group from 50 to 59, the difference becomes much more pronounced. In both of these illustrations, zero on the ordinate scale represents the average of both men and women in the 20–29 group.

Not all the results have been tabulated as yet, but as additional tests are examined, they are found to fall in line with those already tabulated; and there is little likelihood of any major change in trend being encountered as the tabulation proceeds. The interpretation of the losses at various frequencies is rather difficult except for specialists, since the evaluation of the effect on one's ability to hear in any particular band of frequencies is a function of many factors. It has been found, however, that one's ability to understand speech can be determined from the average of his hearing losses at 440, 880, and 1,760 cycles as compared with good young ears. If this average is 25 decibels, there may be some difficulty in hearing in auditoriums and churches, while if it is 45 decibels, there may be difficulty in hearing in direct conversation.

By use of these figures, the tests indicate that about 1 out of 25 persons has difficulty in hearing in auditoriums; 1 in 125 will have some difficulty in direct conversation; and 1 in 400 over the telephone. Two out of five men between 50 and 59 will have a loss of at least 25 decibels at 3,520 cycles, while only one in five women—half as many—will have as great a loss at this frequency. It was found, also, that about 1 in 25 of the group from 10 to 19 had a loss of at least 25 decibels at 7,040 cycles. This figure assumes importance because it has been found that young people with a hearing loss of this amount will often tend to become progressively worse in later years, but that if remedial measures are taken immediately, the hearing impairment may be largely checked.

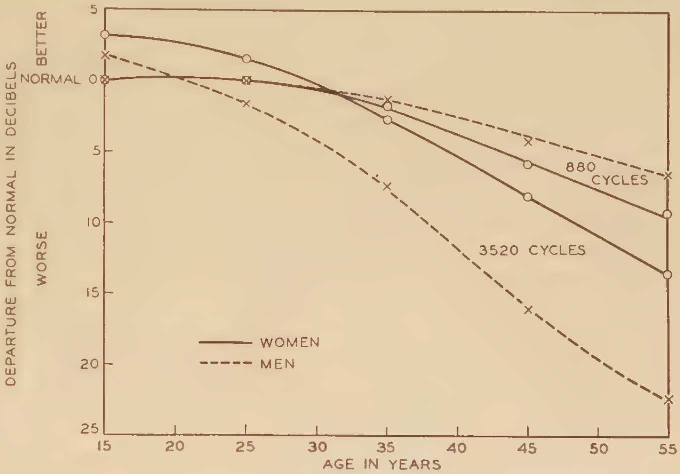


Figure 1. Variation in hearing loss with age for men and women at 880 and 3,520 cycles

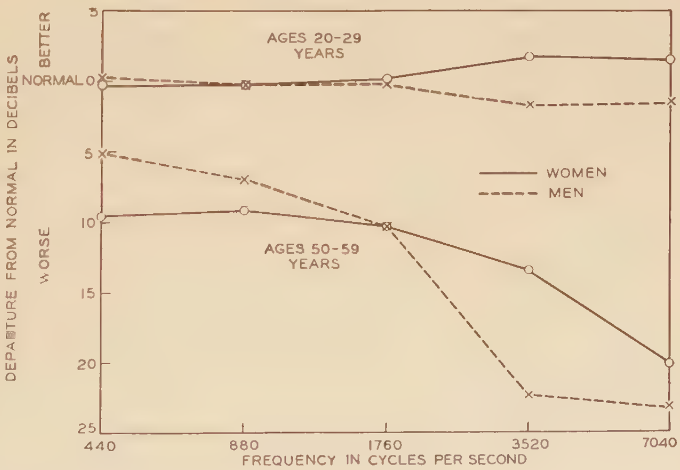


Figure 2. Variation in hearing loss with frequency for men and women in the age groups 20–29 and 50–59

Excerpts from an article of the same title by H. C. Montgomery, acoustical research department, Bell Telephone Laboratories, Inc., New York, N. Y., and published in the *Bell Laboratories Record*, December 1939, pages 98–103

Of Current Interest

Forum of Youth and Industry

"OPPORTUNITY for youth in building the World of Tomorrow" was the theme of a dinner meeting held by the General Motors Corporation, May 6, 1940, in the company's exhibit building at the New York World's Fair. The meeting was attended by several hundred invited guests, including college students, presidents, and faculty members from some 80 representative eastern, southern, and middle-western colleges, as well as from several General Motors apprentice and training schools.

The prearranged after-dinner program included talks by Alfred P. Sloan, Jr., chairman of the board, William S. Knudsen, president, and Charles F. Kettering (A'04, F'14), vice-president in charge of research, of General Motors. The program also included a panel discussion of specific student questions which were answered by Karl T. Compton (F'31), president of Massachusetts Institute of Technology, Cambridge; Ernest M. Hopkins, president of Dartmouth College, Hanover, N. H.; General Hugh S. Johnson; and Doctor Kettering.

Each student had been asked prior to the dinner to send in one or two questions. Hundreds of questions were submitted, and a group of the most pertinent was selected for use in the forum which was conducted by Clifton Fadiman, literary critic and radio personality. This part of the program was conducted in "question and answer" fashion, with Mr. Fadiman stating the questions and one or more members of the forum board answering. With the thought that the questions and answers may be of interest and value to AIEE Enrolled Students, they are presented here; no attempt has been made to record verbatim answers, but the summarizing answers are believed to embrace the essential substance of those given. The person answering is indicated by initials at the end of each answer.

1. *Which counts more in getting a job—a letter on your sweater, or the letters on a Phi Beta Kappa key?* No good employer will look at either—HSJ.

2. *We face the paradox of want in the midst of plenty. Is youth's answer to be found in government action or in the efforts of private enterprise?* The answer appears to be in government action now, but try a slightly divergent course from now on—HSJ.

3. *Has industry reached its peak of expansion, or are there new horizons?* Industry has not even started yet; is now only in its "covered wagon" days—CFK.

4. *What about the profit motive—is there any substitute for it as a vital force in stimulating progress?* INTELLIGENT self-interest is the best motive in stimulating progress; it is possible even to love money INTELLIGENTLY—EMH.

5. *If technological improvement continues will not more and more men be thrown out of work as time goes on?* No. Every new thing developed creates more jobs. Although technological improvement may create unemployment in specific instances, in general it creates many more jobs than it destroys—KTC.

6. *Is it still possible to jump many rungs on the way up the ladder by marrying the boss' daughter?* Don't jump too many rungs; the ladder might break—CFK.

7. *Is it reasonable to expect expansion in industry alone to absorb the millions reported as unemployed, plus college and high-school graduates?* Of course; the only question is in getting started—CFK. (HSJ cited statistics in support of this answer.)

8. *Are the chances greater with a large institution or with a small, more personalized company?* Depends on the individual capacities and tendencies; some men progress faster with large companies, and others with smaller organizations—HSJ.

9. *If business and industrial expansion were free to follow its natural course would it be sufficient to absorb our idle men, money, and materials?* It would go a long way toward achieving that end—KTC.

10. *Can a young man of intelligence but little formal education work his way to the top or is a college education becoming a prerequisite to high executive leadership?* Formal education not necessary; may even be harmful to some men—EMH. Although a formal education is not necessary, the man with formal education has far better chances—KTC.

11. *Would there be more jobs for youth if industrial activities were planned under government supervision?* We must have more government regulation, but not substitution of governmental enterprise for private enterprise; governmental regulations should prevent abuses, but not stifle initiative—HSJ.

12. *Can I capitalize on a college education in the factory or should I hold out for an office job?* Graduates must have experience and learn how to get along with people in order to progress in either type of job; a college education is valuable both places—CFK. Most graduates want shop jobs first in order to obtain experience—KTC.

13. *With increasing relationship between government and industry isn't there a need in government service for young men equipped with a background of industrial experience?* Definitely yes. Unfortunately the trend is now in the other direction, probably because of the lower salary ceilings in government—KTC. Our government doesn't reward government leaders properly—HSJ.

14. *What about social prestige as help in getting ahead in business and industry?* Ability is most important, especially in higher executive positions—KTC.

15. *What can industry do toward raising the standard of living by making it possible for more people to buy more?* More people must produce more and to do that must produce more efficiently—KTC.

16. *Is it fair for business and industry to ask a college graduate to start at the same pay as any other beginner?* No. Because of his better training and equipment the college graduate should receive more—KTC. As in any other race, the stronger man should be willing to give a "handicap"; and since his chances to succeed are better, the college graduate should be willing to start at the lower salary—HSJ.

17. *Are there opportunities in industry for graduates from a general arts course?* Liberal-arts graduates are more common in executive positions—EMH.

18. *Who is going to pay for all those new roads shown in the Futurama?* These kids here—HSJ.

19. *Mr. Knudsen's booklet "If I Were 21" advises us to work with our hands but I have absolutely no mechanical aptitude. What should I do about it?* Most cases of "lack of mechanical aptitude" are only lack of practice or fear, neither of which constitute true lack of mechanical aptitude—CFK.

20. *To what extent is the technical student limited to his particular specialization after entering industry?* About 50 per cent of technical graduates follow the specialties of their training; the other 50 per cent are found in all other types of positions—KTC.

21. *Does industry prefer to train men directly out of college or is graduate training (such as is given by schools of business administration) more desirable?* Graduate training helps some men in some jobs; but not every man is benefited by graduate training or even by any college training at all—EMH.

22. *Can I get along as well in business if I follow high social and ethical standards as I could if I didn't?* NOBODY gets along in ANY stratum of society on low standards—HSJ.

23. *Are there any changes needed in our educational system to prepare youth more adequately for business and industry?* Changes are always needed—EMH. Changes are needed to keep the educational program up to date, and to keep the teachers alive—KTC.

DOCTOR KETTERING CITES NEED FOR NEW PROJECTS

Doctor Kettering, whose address constituted the concluding event of the evening,

warned that any attempt to chart the future was impossible. Pointing to the inability of past generations to forsee the tremendous advances of modern industry, he told the students it was equally futile "for us to try to imagine what the future will be, let alone plan it. All we can do is prepare ourselves to take full advantage of what the future will bring. Our over-all ability is the only thing that really counts.

"We have excesses of men, money, and materials," Doctor Kettering said. "All that we lack today are new projects—new inventions, new products, new activities.

"We need new things more than ever before. With our excess of men, money, and materials, we need new opportunities to put them to work. The discovery of a few fundamental facts might easily be the basis for new industries which will keep us all busy for years to come, just as they have in the past."

Honors • • • •

Egleston Medal Awarded for 1940

The 1940 Egleston Medal of the Columbia University School of Engineering has been awarded to Grover Loening, president of the Grover Loening Aircraft Company, Garden City, N. Y., inventor of the strut-braced monoplane, and holder of many airplane patents. He received the degree of civil engineer from Columbia in 1911.

Founded in 1939, the Egleston Medal is awarded annually to a Columbia alumnus for distinguished engineering achievement (*EE, Jan. '40, p. 44*). The medalist is chosen by the board of managers of the Engineering Alumni Association, of which A. Dexter Hinckley (A'27, M'38) assistant to the dean of the engineering faculty, Columbia, is executive secretary.

Franklin Institute Awards

Presentation of 1940 medal awards by the Franklin Institute was made May 15, 1940, at "Medal Day" exercises in Philadelphia, Pa., which were followed by a dinner in honor of the medalists. The medals presented and the recipients are as follows:

Franklin Medal—A. H. Compton, University of Chicago, for his experiments on properties of X rays and in particular for his discovery of the "Compton effect"; L. H. Baekeland, retired president, The Bakelite Corporation, New York, N. Y., for contributions to improvement of the industrial arts and in particular for the invention and manufacture of Bakelite.

Elliott Cresson Medal—F. M. Becket, president, Union Carbide and Carbon Research Laboratories, New York, N. Y., for developments in production of low-carbon ferro alloys, and also for contributions in electrometallurgy; R. R. Williams, Bell Telephone Laboratories, New York, N. Y., for researches upon vitamin B_1.

Louis E. Levy Medal—jointly to Charles Rosenblum, Princeton University, and J. R. Flagg, University of Rochester, for their paper "Artificial Radioactive Indicators".

George R. Henderson Medal—W. E. Woodard, Lima Locomotive Works, Inc., New York, N. Y., for contributions in steam locomotive design.

John Price Wetherill Medal—Laurens Hammond, president, Hammond Instrument Company, Chicago, Ill., for the inventive skill displayed in the development of the Hammond organ; jointly to E. E. Kleinschmidt (M'22) president, Kleinschmidt Laboratories, Highland Park, Ill., and H. L. Krum (A'12, F'27) (Teletype Corporation, Chicago, Ill.) Beverly Hills, Calif., for their part in the development of the teletypewriter.

Edward Longstreth Medal—jointly to Leopold Godowsky, Jr., and L. D. Mannes, Eastman Kodak Company, Rochester, N. Y., for development and processing of Kodachrome film; Games Slayter, Owens-Corning Fiberglas Corporation, Newark, Ohio, for improved methods and apparatus for making spun and blown glass filaments; R. C. Templin, Aluminum Company of America, New Kensington, Pa., for the development of the Templin automatic autographic deformation recorder; M. M. Upson, president, Raymond Concrete Pile Company, New York, N. Y., for contributions to the scientific development of foundation engineering and construction.

Certificate of Merit—jointly to G. H. Ernsbarger, Honolulu, T. H., and F. L. McCarty, Ogden, Utah, for development of a device for loading a jigging conveyor.

ATLANTIC REFINING COMPANY HONORED

For its pioneer work in relation to refining, transporting, and marketing petroleum products, the Atlantic Refining Company, Philadelphia, Pa., was honored at a dinner given by the Franklin Institute, April 29, 1940.

Among the achievements noted on the citation presented to the company is "novel developments in the construction and propulsion of ocean-going tankers."

These steam-turbine-electric ships are unique in that, contrary to marine tradition, both practices and equipment common to modern land power plants were utilized. These included high-pressure (625-pound 835-degrees-Fahrenheit) boilers, standard turbine generators (4,500 kw, 60 cycles, 2.3 kv at 3,600 rpm), synchronous-induction propulsion motors (5,000 shaft horsepower at 90 rpm, 2.3 kv, three phase), deep-well cargo pumps (300 horsepower, 2.3 kv, 1,750 rpm), and induction motors for steering-gear oil pumps.

Awards for "Amplidyne" Development. Charles F. Coffin Foundation Awards, conferred annually by the General Electric Company upon employees for outstanding contributions to the company and the electrical industry, recently were given to Kenneth K. Bowman, M. A. Edwards, and Francis Mohler, for improvements in control equipment made possible by the development of the "amplidyne" generator. Three papers on this subject were presented at the industrial power applications session of the AIEE winter convention, New York, N. Y., January 22–26, 1940, and will be published in the AIEE TRANSACTIONS. Mr. Edwards was co-author of two of the papers and Mr. Bowman co-author of one.

Education • • •

Stevens Management Conference. The tenth of the series of annual conferences of business and engineering administrators held by Stevens Institute of Technology, Hoboken, N. J., at its Engineering Camp at Johnsonburg, N. J., is to be a management conference, to be held June 22–30, 1940. Four series of morning conferences, two of which may be attended without conflict of hours will deal with management control industrial psychology, applied economics, and labor. Evening discussion sessions will be held for the entire group. The conference will be limited to 50 full members, 50 associates each nominated by a full member, and a group of teacher members. The advisory committee planning the conference includes R. M. Gates (M'35) vice-president, The Superheater Company, New York, N. Y.; L. M. Goldsmith (M'26) chief engineer, Atlantic Refining Company, Philadelphia, Pa.; H. A. Wagner (A'98, M'03) president, Consolidated Gas Electric Light and Power Company of Baltimore, Md.

Traffic Engineering Fellowships. Two groups of graduate fellowships in street and highway traffic engineering are available at the Bureau for Street Traffic Research, Yale University, according to an announcement by the Bureau. Only employees of state highway departments are eligible for 7 of these fellowships; for 12 others, employees of organizations concerned with engineering aspects of traffic control, or graduate students seeking a career in traffic engineering, may apply. Applicants should write to Maxwell Halsey, associate director, Bureau of Street Traffic Research, Room 311, Strathcona Hall, Yale University, New Haven, Conn.

Industrial Statistics Course. A two-weeks summer course in statistical methods is being offered by Massachusetts Institute of Technology, September 4–14, 1940. The course is intended for those interested in applying the rudiments of modern statistical technique to design and analysis of laboratory experiments and control of the quality of industrial products. Registration is limited to 20 persons, to be accepted in the order of application.

Other Societies •

Valuation Engineers Organize National Society

Planned as a national organization of valuation engineers, the Technical Valuation Society, Inc., was organized and chartered under New York State laws in December 1939 and has established headquarters at 60 Wall Street, New York, N. Y. Its constitution and bylaws are modeled to a considerable extent upon those of the older national engineering societies, particularly in regard to grades of membership, application procedure, and provision for geographical districts.

Objects of the society as stated in its constitution are:

"To establish the recognition of valuation engineering as a professional degree; to promote the intercourse of engineers among themselves and to foster the relations of the accounting branches of valuation work and with official governing bodies; to advance the standard of valuation engineering; to foster valuation-engineering education; and in co-operation with other engineering, technical, and accounting societies to broaden the scope of the valuation engineer."

Chemical Groups Hold Electrical-Insulation Symposium

A symposium on electrical insulation was held as one of the sessions of the annual meeting of the American Chemical Society, Cincinnati, Ohio, April 8–12, 1940. Sponsored by the society's division of industrial and engineering chemistry, the symposium was arranged by the subcommittee on chemistry of the Conference on Electrical Insulation, National Research Council. Of the five papers presented, one, "Dielectric Properties of the Rutile Crystalline Modification of Titanium Dioxide" by L. J. Berberich (A'30, M'36) and M. E. Bell, was also presented at the annual meeting of the Conference on Electrical Insulation, Cambridge, Mass., November 2–4, 1939, and an abstract published in ELECTRICAL ENGINEERING, January 1940, page 33. Brief abstracts of the other papers follow:

Electrical Insulating-Oil Deterioration: Chemical and Electrical Tests, *J. C. Balsbaugh (A'23, M'35), A. H. Howell (A'35), A. G. Assaf.* Studies of the electrical and oxidation stability of two series of related samples of electrical insulating oils have been made. One consists of 11 samples, representing different solvent refining extracts and finishing treatments, from an appropriate distillation cut; the other of 5 samples with varying amount or aromaticities, one of the samples being aromatic-free. These samples were deteriorated by oxidation in the presence of paper and copper in an improved deteriorating system consisting of an all-glass enclosed system, an automatic means for maintaining constant oxygen pressure, and small platinum-tubing cells for making electrical measurements on the oil and the oil-impregnated paper during the deterioration. The results show that the electrical stability and the oxidation stability of an oil are differently affected by the initial chemical constituency and the refining of an oil, and that the electrical loss as a function of oxidation time or oxygen absorbed may start with a rapid increase to a relatively high value to be followed by an equally rapid decrease to a relatively low value with further oxygen absorbed, after which the loss again increases with continued oxidation.

The Dielectric Properties of Some Organic Compounds As Related to Chemical Composition and Physical Structure, *S. O. Morgan, W. A. Yager.* The dielectric constants of polar liquids should be directly derivable from their chemical structure according to simple dielectric theory. In many liquids the observed values differ greatly from those thus calculated. These departures may be due to association or interaction causing the molecules to act as associated pairs or aggregates in which the net electric moment is low because dipoles are so directed as to oppose each other. Also, such differences may be due to the effect of internal friction or viscosity in restricting the motion of dipoles or to solidification which may entirely prevent motion. In the solid state, where on the basis of simple theory no rotation would be expected and consequently low dielectric constants would be the rule, there are many cases of high dielectric constant. The geometry of the molecule is the determining factor in permitting rotation of molecules and high dielectric constant in the solid state. In plastics the polymer molecules as a whole are too large to rotate but motion of polar groups may be possible. Such motions appear to be sufficient to explain observed values of dielectric constant in plastics. A correlation is found between the presence of polar groups and value of dielectric constant in plastics.

The Electric Conduction in Dielectric Liquids, *R. W. Dornte.* The current-voltage relations at high electrical gradients were obtained for dry gas-free heptane and benzene at 23 degrees centigrade. The current measurements were made in both uniform and nonuniform electric fields which were obtained by the use of plane parallel, hemispherical, and concentric cylindrical electrodes. A comparison of the experimental results with the requirements of the thermionic emission theory of conduction was made by means of the slopes of the current-voltage curves. The agreement of the experimentally determined slopes with those calculated by this theory is not satisfactory. The experimental result was generally greater than the calculated slope, indicating that the electron emission was concentrated on sharp points on the electrode surface. This conclusion was substantiated by experiments showing that the currents were not proportional to the electrode areas in uniform electric fields. The current-voltage curves were dependent upon the nature of the electrode surfaces and were influenced by the polish and adsorbed gases, as well as materials which were removed from the cell by repeated washings with the purified benzene or heptane. The current-voltage characteristics of benzene and heptane were reproducible in a given cell but were difficult to produce in different cells. The slope of current-voltage characteristic for heptane was independent of the temperature in the interval 23 to 97 degrees centigrade. The cold-cathode emission of electrons is suggested as a possible mechanism for the electrical conduction in dielectric liquids. In a nonuniform electric field the current was not determined by the voltage gradient at the cathode as required by either of these conduction mechanisms.

Conductivity in Insulators and Its Interpretation, *A. von Hippel (M'37).* The electrostatic classification of matter into conductors and insulators no longer can be vindicated. In every insulator, charges may be transported; the degree of conduction depends not only upon the chemical material used but also upon the treatment it is given, its temperature, the strength and duration of the electric field to which it is subjected, its previous history, and even the metal electrode in contact with it. The paper tries to resolve this complexity of phenomena into a number of elementary processes, for which experimental examples are given. In this way a new understanding of dielectric matter can be built up which should prove helpful for chemical and physical research.

Future Meetings of Other Societies

American Association for the Advancement of Science. Summer meeting, June 17–22, 1940, Seattle, Wash.

American Chemical Society. Fall meeting, September 9–13, 1940, Detroit, Mich.

American Institute of Mining and Metallurgical Engineers. Regional meeting, September 10–13, Salt Lake City, Utah.

American Physical Society. 235th meeting, June 19–20, 1940, Seattle, Wash.

236th meeting, June 20–22, 1940, Pittsburgh, Pa.

American Society for Testing Materials. 43d annual meeting, June 24–28, 1940, Atlantic City, N. J.

American Society of Civil Engineers. Annual convention, July 24–26, 1940, Denver, Colo.

American Society of Heating and Ventilating Engineers. Semiannual meeting, June 17–19, 1940. Washington, D. C.

American Society of Mechanical Engineers. Semiannual meeting, June 17–21, 1940, Milwaukee, Wis.

Applied mechanics division, June 20–21, 1940, Ann Arbor, Mich. Oil and gas power division, June 19–21, 1940, Asbury Park, N. J.

Fall meeting, September 3–6, 1940, Spokane, Wash.

American Transit Association. 59th annual convention, September 23–26, 1940, White Sulphur Springs, W. Va.

Illuminating Engineering Society. 34th annual convention, September 9–12, 1940, Spring Lake, N. J.

Institute of Radio Engineers. 15th annual convention, June 27–29, 1940, Boston, Mass.

Society for the Promotion of Engineering Education. 48th annual meeting, June 24–28, 1940, University of California, Berkeley, Calif.

ASTM 1940 Index Issued. The 1940 edition of the "Index to ASTM Standards, Including Tentative Standards", recently issued by the American Society for Testing Materials, contains information as of January 1, 1940, on the society's 885 standards. Copies of the 152-page publication may be secured without charge from the society's headquarters, 260 South Broad Street, Philadelphia, Pa.

Research Institute Meets. Member representatives of the Industrial Research Institute, affiliate of the National Research Council, met with deans of engineering from a number of American universities at the Institute's annual meeting at Cincinnati, Ohio, April 26–27, 1940. Feature session of the meeting was a panel discussion on how to make industry and university relations in research more effective.

Industry • • • •

Lighting Practice

The Illuminating Engineering Society has just issued "Recommended Practice for the Illumination Performance of Residential Ceiling Luminaires", prepared by its committee on residence lighting. Recommendations cover standards of performance, but do not include construction specifications.

The number of variable factors affecting the efficiency of lighting fixtures makes issuance of detailed construction rules impracticable, although the society made one exception in the case of its specifications for

a portable reading lamp, issued in 1934. The recent report points out that most-favorable seeing conditions are usually provided by a combination of general and special lighting.

A new edition of "Artificial Light and Its Application", 296-page source book, has recently been published by the lamp division of the Westinghouse Electric and Manufacturing Company. The book covers a wide range of lighting applications, including residence lighting. Copies may be obtained for $1.25, or single chapters for 7 cents each, from the company, 150 Broadway, New York, N. Y.

Cathode-Ray Contest. A prize contest for new practical applications of the cathode-ray tube and allied equipment will be conducted by the Allen B. Du Mont Laboratories, Inc., Passaic, N. J., from June 1, 1940, to May 31, 1941. Entries may be made by anyone, at any time during the period, and in any number, but only papers dealing with actual applications will be considered. Applications may be in any field. Prizes of $100, $50, and $25 will be awarded for the three best papers submitted, and $10 will be paid for papers accepted for publication in the Du Mont *Oscillographer*.

Report on Industrial Dermatitis. The National Association of Manufacturers' committee on healthful working conditions has issued a summary of accepted medical knowledge on the subject of industrial dermatitis, which in some form is the cause of more than half the compensation claims for occupational disease. Single copies of the report may be secured free, or quantities at cost, from the committee, at 14 West 49th Street, New York, N. Y

From A E C • •

ITEMS appearing under this heading are from the news service of American Engineering Council.

FPC Publication Details Utility Statistics

Comprehensive facts regarding all public-utility companies in the United States receiving annual electric incomes of $250,000 or more, representing 95 per cent of the industry, are contained in a new publication of the Federal Power Commission, "Statistics of Electric Utilities in the United States, 1938" available at $2 per copy from the Commission. The 500-page volume reports official figures from detailed returns made to the Commission as required by law. A similar volume was issued last year.

The 393 electric-utility companies listed have total assets aggregating $17,220,617,262; utility-plant accounts totaling $14,048,019,026; outstanding securities amounting to $13,546,254,340. In 1938 their electric operating revenues aggregated $2,168,670,032 from the following sources: 19,411,872 residential customers paid $683,341,136 for 16,285,671,000 kilowatt-hours, an average use of 839 kilowatt-hours at an average cost of 4.20 cents. Commercial and industrial users numbering 3,689,477 paid $1,069,932,195 for 59,182,940,000 kilowatt-hours, an average of 1.81 cents per kilowatt-hour.

The Commission has ordered 31 utility companies to show cause for their failure to comply with provisions in its uniform system of accounts requiring the reclassification of plant accounts on the basis of original cost.

Supreme Court Stops Sale of Hetch-Hetchy Power

Final settlement of a dispute between the Federal Government and the city of San Francisco that dates back to 1923 was rendered when the United States Supreme Court on April 22 declared invalid a contract between the city and the Pacific Gas and Electric Company for the distribution of electric power generated as a by-product of the Hetch-Hetchy municipal water development.

In 1913 Congress authorized the city to use lands included in the Yosemite National Park and the Stanislaus National Forest as a source of its water supply on condition that none of the power to be generated as a by-product should be sold to any corporation or individual except a municipality or water or irrigation district. As a temporary measure, the city contracted with the power company to act as its agent in transmitting and distributing the power, and has continued this arrangement ever since.

In 1923, and at intervals thereafter, the Federal Government has warned the city that this agreement violates the conditions imposed, and San Francisco has several times held elections on the question of establishing a municipal power system, but this proposal has each time been defeated. The latest of these was in 1937, after Secretary of the Interior Harold L. Ickes had warned the city to cease violating the act of 1913. Whereupon the Federal Government applied to the courts for an injunction prohibiting further operation of the power plants. This was granted by a District Court, overruled by a Court of Appeals, and has now been sustained by the Supreme Court.

The practical effect of the decision is to force San Francisco to choose immediately between setting up a municipal power system or ceasing to operate the Moccasin and early Intake power plants in the Hetch-Hetchy valley.

More Utilities Contest "Death Sentence"

Efforts of the Securities and Exchange Commission to break up large and complex holding-company structures in accordance with provisions of the Public Utility Holding Company Act of 1935 are meeting with continued resistance on the grounds of unconstitutionality of the statute. In addition to the Engineers Public Service Company (noted last month) three other organizations have replied to SEC orders to submit reorganization plans with this same contention. These are Electric Bond and Share Company, United Gas Improvement Company, and Commonwealth and Southern Corporation.

United Gas Improvement Company has also attacked SEC's method of procedure; it contends that instead of directing holding companies to submit plans for reorganization the agency first should have prepared its own plans, which then should have been reviewed in public hearings.

Letters to the Editor • • •

INSTITUTE members and subscribers are invited to contribute to these columns expressions of opinion dealing with published articles, technical papers, or other subjects of general professional interest. While endeavoring to publish as many letters as possible, Electrical Engineering reserves the right to publish them in whole or in part or to reject them entirely. Statements in letters are expressly understood to be made by the writers; publication here in no wise constitutes endorsement or recognition by the AIEE. All letters submitted for publication should be typewritten, double-spaced, not carbon copies. Any illustrations should be submitted in duplicate, one copy an inked drawing without lettering, the other lettered. Captions should be supplied for all illustrations.

Post-Convention Cruise

To the Editor:

The post-convention cruise was a success in program if not in numbers. The astounding number of three accepted the rigors of the cruise, and risked life and limb against the wind, the sea, and submarines. Those participating were: Mrs. Julia Mullaney, of New York City and Daytona Beach; Miss Mildred Clark, of Orange, N. J.; and the writer.

The SS George Washington left New York at 1:00 p. m. Saturday, January 27, and arrived in Norfolk the following morning. There were about 90 passengers aboard, about half of whom were United States Navy recruits going to the medical training school in Portsmouth, Va. The group certainly spoke well for the exceptionally high type of young men entering the services at the present time. All went smoothly until about 9:00 p. m. when the wind howled and the boat rocked and the waves did beat themselves against the hull, and caressed the portholes and first deck. Many succumbed, but the little group of three stood firm and resolute. Came the dawn, and with it, a beautiful day and a calm sea for the remainder of the trip.

Upon arriving at the wharf, the ship's employees had a little difficulty in placing the gangplank at the correct angle, but finally succeeded in making it into an Alpine climber's nightmare, and the passengers struggled ashore. The AIEE group was met here with a car and two guides—one to drive and the other to lecture—due to the presence of ice and snow on the highways. The tour included Norfolk, Newport News, Old Point Comfort, Jamestown, and Williamsburg. At Newport News, there were the shipyards; at Old Point Comfort, Fortress Monroe and the Chamberlain Hotel; at Jamestown, the statues of John Smith and Pocahontas. as well as the original church

tower dating from the first settlement at Jamestown in 1607. The graves of many historic persons are in the old church, which has been restored to its former condition.

At Williamsburg, lunch was served at the Inn, and after lunch the tour continued with a visit to the restored buildings of colonial times. These are new brick buildings built on the same plans as the originals. Inside are the offices, committee rooms, and assembly halls of the rulers of the Jamestown colony. The furnishings are in accordance with inventories which have been discovered from time to time in colonial records, and in cases where original pieces were not obtainable, reproductions have been wrought with painstaking care. There were beautiful glass chandeliers, furniture of fine woods, exquisitely fashioned silver fixtures and tableware, and fine porcelains, draperies, and rugs. For any one interested in antiques of early colonial times, Williamsburg is well worth seeing. In fact, after going through these buildings and viewing the furnishings, and seeing the hostesses clothed in period costume, the visitor begins to feel that he himself is back in that early time, and is mildly shocked to see a hostess reading a modern magazine!

After spending about three hours in Williamsburg, it was time to continue back to Virginia Beach where the hotel was waiting. And what a hotel! A swimming pool, sumptuous meals, luxurious rooms, and the best of service. The party stayed over night at the hotel, and had the following day free for visiting the shops in Norfolk, walking along the snow-swept beach, or just enjoying the comfort of the hotel. At four in the afternoon, the car returned to the hotel in order to take the group to the ship for the return voyage. It was with many regrets that the wharf was seen to slip away into the darkening shadows of the night, and the crunching of ice in the outer harbor was heard.

The sail up to New York was as calm as a mill-pond, and finally the hustle and bustle of the great harbor was seen. It was like living in the past and suddenly coming face to face with the fast tempo of the present. A thoroughly worth-while trip, and it was extremely regrettable that more could not disregard the possibly unseasonable weather, and take it. If they knew what they were missing, they would have overlooked wind, tide, and storm.

A. M. SALISBURY (A'37)

(Westfield Gas and Electric Company, Westfield, Mass.)

"Reciprocal Addition"

To the Editor:

Those who handle reciprocals in making calculations for parallel resistors or series capacitors may find the following mathematical device of interest:

Let it be desired to find the parallel resistance of three resistors, of 1 ohm, 2 ohms, and 3 ohms, respectively. By the standard procedure, the total conductance is given by

$$\frac{1}{1}+\frac{1}{2}+\frac{1}{3}=\frac{6+3+2}{6}=\frac{11}{6}\text{mhos}$$

Hence the resistance is 6/11 ohms.

By introducing a new symbolism, the necessity of considering conductances or reciprocals is avoided, and the procedure is considered as a special type of addition of fractions, that is, "reciprocal addition." As in other symbolic innovations, the actual numerical work is not lessened, but the amount of writing is decreased, and thinking may be clarified somewhat.

Let us define the symbol

$$\text{Recip}(R_1R_2R_3R_4\ldots)\equiv\frac{1}{\frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{R_3}+\frac{1}{R_4}+\ldots}=R$$

In the above example, then,

$$R=\text{Recip}\,(1,2,3)=$$

$$\text{Recip}\left(\frac{1}{1},\frac{2}{1},\frac{3}{1}\right)=\text{Recip}\left(\frac{6}{6},\frac{6}{3},\frac{6}{2}\right),$$

and by adding the *denominators*, we get directly 6/11 ohms.

The procedure is therefore: (1) expression of each term in fractional form, (2) reduction to the *least common numerator*, and (3) addition of the *denominators*.

For a demonstration in general terms, let $\prod_1^n R_i$ represent the product of R_1 to R_n. Then

$$\text{Recip}(R_1R_2\ldots R_n)=\text{Recip}\left(R_1\frac{\prod_1^n R_i}{R_1R_2\ldots R_n},\ R_2\frac{\prod_1^n R_i}{R_1R_2\ldots R_n},\ldots R_n\frac{\prod_1^n R_i}{R_1R_2\ldots R_n}\right)=$$

$$\text{Recip}\left(\frac{\prod_1^n R_i}{R_2R_3\ldots R_n},\ \frac{\prod_1^n R_i}{R_1R_3\ldots R_n},\ldots\frac{\prod_1^n R_i}{R_1R_2\ldots R_{n-1}}\right)$$

and applying step 3,

$$\text{Recip}(R_1R_2\ldots R_n)=$$

$$\frac{\prod_1^n R_i}{R_2R_3\ldots R_n+R_1R_3\ldots R_n+\ldots+R_1R_2\ldots R_{n-1}}=$$

$$\frac{1}{\frac{R_2R_3\ldots R_n}{\prod_1^n R_i}+\frac{R_1R_3\ldots R_n}{\prod_1^n R_i}+\ldots+\frac{R_1R_2\ldots R_{n-1}}{\prod_1^n R_i}}=$$

$$\frac{1}{\frac{1}{R_1}+\frac{1}{R_2}+\ \ldots\ +\frac{1}{R_n}}$$

ELLIS BLADE (A'35)

(Technical consultant, John Chatillon and Sons, New York, N.Y.)

The Use of the Millibar in Weather Bureau Reports

To the Editor:

This has reference to the letter by Clayton H. Sharp, in ELECTRICAL ENGINEERING, March 1940, page 124.

The engineering societies should commend the Weather Bureau for their adoption of the international standard "millibar" because it is in line with modern progress.

Nothing deserves to be retained merely because it is "ancient." Each thing should stand on its own inherent merits. The millibar has the advantages of logic; it is scientifically correct; it is convenient to use, and is really an international standard.

The cgs system of units and the metric system are not "theoretical" but very practical, as I know by my own use for many years.

The Weather Bureau is to be supported in the move to use more widely the international units and it is to be hoped that none of the great engineering societies will make the mistake of opposing this real progress.

ARTHUR BESSEY SMITH (A'04, F'22)

(Chief research engineer, Associated Electric Laboratories, Inc., Chicago, Ill.

"Electromagnetic Problems in Electrical Engineering"

To the Editor:

One who has occasion to read widely in electromagnetic theory as concerns its application in electrical-machine design cannot help but note how little, comparatively speaking, has been done in connection with field-mapping problems in regions containing two or more materials of different permeabilities. Among the major contributors to this field have been G. F. C. Searle, W. Rogowski, T. Lehmann, E. Roth, and B. Hague. The subject is summarized in the latter's unique and important "Electromagnetic Problems in Electrical Engineering" which is, practically speaking, the only reference book in this branch of electrical engineering. For this very reason errors in this text are of special concern. It is the purpose of this letter to point out one such, rendered the more important by the fact that this incorrect formula has been used by others.

On pages 275–9 Hague discusses the problem: Given an isolated linear conductor of radius a and permeability μ contained in a medium of unit permeability, carrying a direct current of magnitude I and density δ, to find the vector potential interior and exterior to the conductor. The solution given,

$$A_e=-2I\left(\log\frac{r}{a}+\frac{1}{2}\right)\quad\text{when } r>a$$

$$A_i=-\mu I\frac{r^2}{a^2}\qquad\text{when } r<a$$

is incorrect.

It is not difficult to find Hague's error. On page 276 it is stated that

> "Again, at $r=a$ the vector potential in the air must be $\frac{1}{\mu}$ times that in the permeable rod; in other words, the induction, in this problem entirely peripheral, must be discontinuous on the two sides of the boundary since the normal or continuous component of B is zero thereat."

This is not true. At a given point on an interface between two media of different permeability, the vector potential* in each

* See for example, STATIC AND DYNAMIC ELECTRICITY, W. R. Smythe, page 280, equation 3.

medium is the same, and is always so regardless of whether or not the induction is totally tangential (as in this case).

In pages 278–9 Hague gives a second solution which is also incorrect. Here the total current is considered to be an aggregate of parallel current filaments and the total vector potential is obtained by summing the vector potentials due to each of the individual filaments. But in doing so one is no longer dealing with a filament in a medium of permeability μ but rather with a filament in a medium of permeability μ surrounded by another of unit permeability and the interface between these two produces magnetic effects which are completely neglected in the treatment of the book. Although the effects so produced cancel when all filaments are treated, the procedure of the solution is misleading and will give incorrect solutions when applied to conductors of other shapes. The solution obtained by this method agrees with that obtained by the first method because the erroneous boundary solution is again used. On page 278 we have,

"When P is inside the section of the bar μ is retained; when P is outside the section the right-hand side is divided by μ."

The correct solution of this problem is the following. We seek a solution A which satisfies the following conditions:

$$(a).\quad \frac{d^2A_i}{dr^2}+\frac{1}{r}\,\frac{dA_i}{dr}=-4\pi\mu\delta \qquad \text{when } r<a$$

$$(b).\quad \frac{d^2A_e}{dr^2}+\frac{1}{r}\,\frac{dA_e}{dr}=0 \qquad \text{when } r>a$$

$$(c).\quad \frac{1}{\mu}\,\frac{dA_i}{dr}=\frac{1}{\mu}\,\frac{dA_e}{dr} \qquad \text{when } r=a$$

$$(d).\quad A_i=A_e \qquad \text{when } r=a$$

(e). A is finite within the conductor.

Now (a) and (b) are well-known equations, and solutions satisfying (e) are:

$$A_i=-\delta\mu\pi r^2+C_1$$
$$A_e=C_2\log r+C_3$$

To determine the constants we employ (c) and (d) together with the stipulation, the datum of A being arbitrary, that $A_i=0$ when $r=0$. Applying these conditions and recalling that $\pi r^2\delta = I$ we obtain

$$A_e=-2I\left(\mu\log\frac{r}{a}+\frac{\mu}{2}\right) \qquad \text{when } r\geq a$$

$$A_i=-\mu\, I\frac{r^2}{a^2} \qquad \text{when } r\leq a$$

If $\mu=1$ we obtain the correct solution of Hague's problem.

$$A_e=-2I\left(\log\frac{r}{a}+\frac{\mu}{2}\right) \qquad \text{when } r\geq a$$

$$A_i=-\mu I\,\frac{r^2}{a^2} \qquad \text{when } r\leq a$$

Comparison of this solution with that given by Hague reveals a difference in the expression for A_e.

THOMAS J. HIGGINS (M'40)

(School of electrical engineering, Purdue University, West Lafayette, Ind.)

Books Received

The following new books are among those recently received at the Engineering Societies Library. Unless otherwise specified, books listed have been presented by the publishers. The Institute assumes no responsibility for statements made in the following summaries, information for which is taken from the prefaces of the books in question.

THE HISTORY OF THE INSTITUTION OF ELECTRICAL ENGINEERS (1871–1931). By R. Appleyard. Institution of Electrical Engineers, Savoy Place, London, 1939. 342 pages, illustrated, tables, 10 by 7½ inches, cloth, 18s6d. The history of the Institution, as here presented, is an account of the development of electrical engineering during 60 active years. In that development the Institution has played an important part, and this record of its work, the matters discussed by it, and the eminent engineers who were members, is a valuable contribution to engineering history.

THE MEASUREMENT OF ALTERNATING-CURRENT ENERGY. By D. T. Canfield. McGraw-Hill Book Company, New York and London, 1940. 210 pages, illustrated, 8½ by 5½ inches, cloth, $2.00. Answers the fundamental questions about devices for the measurement of a-c energy, including explanations of the inductive load adjustment, the retarding force, and the recording mechanism. Meter constants and ratios are discussed. Also presents the development and application of a method of proving the correctness of any proposed metering combination.

THEORY AND PRACTICE OF ELECTRON DIFFRACTION. By G. P. Thomson and W. Cochrane. New York, Macmillan Company, 1939. 334 pages, illustrated, 9 by 6 inches, cloth, $6.00. The discovery of the diffraction of electrons by a crystal has produced developments in two widely different fields. The author covers in this volume both aspects of the discovery, first as the most direct experimental proof of the wave theory of matter, and second as a means of studying the properties of thin surface layers. Both theoretical considerations and practical applications are discussed.

THE TECHNICAL COLLEGE. By W. A. Richardson. New York and London, Oxford University Press, 1939. 495 pages, illustrated, 9 by 6 inches, cloth, $5.00. The principal of a large English technical college surveys the field with a view toward increasing the efficiency of this type of education. He describes the organization and administration of the technical college, the physical equipment, and the types of students to be considered. Relations with industry are discussed, among other problems, and future developments are considered.

HEATING, VENTILATING, AIR CONDITIONING GUIDE, volume 18, 1940. American Society of Heating and Ventilating Engineers, New York, N. Y. 1088 pages, illustrated, 9 by 6 inches, cloth, $5.00. Annual summary of the scientific and practical information needed by heating and ventilating engineers, kept up to date by constant revision. Needs of designers and installers of apparatus, both for domestic and industrial purposes, are considered. A new chapter on unit air-conditioners, cooling units, and attic fans has been added. Also contains a manufacturers' section, which lists apparatus and materials, and the membership list of the Society.

ELECTRIC TRANSPORTATION. By F. R. Thompson. International Textbook Company, Scranton, Pa., 1940. 427 pages, illustrated, 9½ by 6 inches, cloth, $4.00. Presents methods of applying electrical equipment in passenger and freight transportation. Includes selection of general classes of equipment, function of individual groups of parts, commercially practicable ratings and limitations, and operating results. Transportation by city surface cars and busses, subway and elevated systems, and main railways is discussed.

PRACTICAL ELECTRICITY. By T. Croft, revised by G. H. Hall. Fourth edition. McGraw-Hill Book Company, New York, 1940. 701 pages, illustrated, 8½ by 5½ inches, cloth, $3.00. Covers the fundamentals of electricity, with illustrations by practical applications in everyday life. Calls for no special mathematical knowledge and is adapted to home study.

ASTM STANDARDS, INCLUDING TENTATIVE STANDARDS, 1939. Three volumes. Volume 1, Metals, 1308 pages; Volume 2, Nonmetallic Materials, Constructional, 1217 pages; Volume 3, Nonmetallic Materials, General, 1175 pages. American Society for Testing Materials, Philadelphia, Pa., 1939/1940. Illustrated, 9½ by 6 inches, cloth, $8.00, any one part; $15.00, any two parts; $22.00, all three parts. With this issue, a change in the method of publication has been adopted. Hereafter, the standards and tentative standards will be issued collectively, every three years, in the form of this issue. Individual parts may be purchased. Supplements will be issued between editions.

1. TABLE OF THE FIRST TEN POWERS OF THE INTEGERS FROM 1 TO 1,000. Project for the Computation of Mathematical Tables. Works Progress Administration, New York, under the sponsorship of the National Bureau of Standards, Washington, D. C., 1939. 80 pages, tables, 14 by 8½ inches, paper, $0.50 2. TABLES OF THE EXPONENTIAL FUNCTION e^x. Federal Works Agency, Works Project Administration for the City of New York, conducted under the sponsorship of the National Bureau of Standards, 1939. 535 pages, tables, 11 by 8 inches, cloth, $2.00. These publications are the first of a series of mathematical tables. Both are printed in type-script. The second contains tables of the exponential from −2.5000 to 1.0000 at intervals of 0.0001 to 18 decimals; from 1.0000 to 2.5000 at intervals of 0.0001 to 15 decimals; from 2.500 to 5.000 at intervals of 0.001 to 15 decimals; and from 5.00 to 10.00 at intervals of 0.01 to 12 decimals.

WATT-HOUR METERS. By W. C. Wagner. International Textbook Company, Scranton, Pa., 1939. Three sections paged separately, illustrated, 8 by 5 inches, leather, $1.70. Instruction book for metermen on the varieties and applications of watt-hour meters. The characteristics of each type, the construction of various commercial patterns, installation and testing, wiring, etc., are described.

ACOUSTICAL SOCIETY OF AMERICA JOURNAL, CUMULATIVE INDEX, volumes 1–10, 1929–1939. Published for the Acoustical Society of America by the American Institute of Physics, Lancaster, Pa., and New York, N. Y., 1939. 131 pages, 10½ by 8 inches, paper, $3.00. Contains author and subject indexes to the first ten volumes of the Journal, as well as to books and papers on acoustical subjects that appeared elsewhere during 1937 and 1938 and were referred to in the Journal.

TELEVISION, THE ELECTRONICS OF IMAGE TRANSMISSION. By V. K. Zworykin and G. A. Morton. John Wiley and Sons, New York, 1940. 646 pages, illustrated, 9 by 6 inches, cloth, $6.00. Most of the literature on television exists only in periodicals. The present work is intended as an integrated, detailed survey of the field. It presents the fundamental physical phenomena involved in television, analyzes the components of the electronic television system based upon the storage principle, and finally describes the television system used in the RCA-NBC project. Brief bibliographies accompany many chapters.

WRITING THE TECHNICAL REPORT. By J. R. Nelson. McGraw-Hill Book Company, New York and London, 1940. 373 pages, diagrams, etc., 9½ by 6 inches, cloth, $2.50. Fundamental considerations that bear on the design and composition of a report are reviewed, and specific directions given for the setup. Several annotated illustrative reports are included. A procedure is outlined for the critical examination of reports, including some typical cases, and suggestions for classroom procedure, made.

AN AIR-CONDITIONING PRIMER, THE A B C OF AIR CONDITIONING. By W. H. Stangle. New York and London, McGraw-Hill Book Company, 1940. 236 pages, illustrated, 9½ by 6 inches, cloth, $2.50. Tells what air conditioning is and what it can do, explains its technical fundamentals and the methods of applying them, and describes types of equipment available. Includes examples of design computations. Some 30 tables of data are appended.

ALTERNATING-CURRENT CIRCUITS. By K. Y. Tang. International Textbook Company, Scranton, Pa., 1940. 438 pages, diagrams, etc., 9½ by 6 inches, cloth, $4.00. Intended as an introductory course in the study of circuit analysis, the material here presented should precede the study of a-c machinery, power, and communication networks. The physical nature of circuit elements and the principles and laws of electric circuits are covered, with emphasis on the effects of the circuit elements on the flow of current and the relations of instantaneous values. Problems.

ELECTRIC DISTRIBUTION FUNDAMENTALS. By F. Sanford. McGraw-Hill Book Company, New York and London, 1940. 242 pages, illustrated, 9½ by 6 inches, cloth, $2.50. Written from a nonengineering viewpoint, this book gives the perspective, development, and economic background of electric distribution as a part of the general system of electric supply. Outlines features of both the utility distribution, and the industrial and inside-wiring branches of service to the outlet. Practical design problems are included, with solutions based on graphical methods rather than on engineering mathematics.

ELECTRICAL METERMEN'S HANDBOOK, Fifth edition, 1940. Edited and published by Edison Electric Institute, New York. 354 pages, illustrated, 10 by 8 inches, cloth, $3.60. Completely revised edition of the "Handbook for Electrical Metermen", the fourth edition of which appeared in 1923. Primarily for the practical meterman and the meter engineer, it contains the basic principles, diagrams of the usual connections for all types of metering, descriptions of laboratory equipment and procedure, full descriptions of all American meters of modern types, and complete tables of constants for all types of meters in current use.

Institute Activities

1940 Summer Convention Program Completed

THE program for the AIEE summer convention, which will be held in Swampscott, Mass., June 24–28, with headquarters in the New Ocean House, provides for a busy and profitable week, yet not without ample opportunities for sports, trips, and social recreation. The business program is comprised of ten technical sessions, a general session, seven technical conferences, the annual meeting, the conference of officers, delegates, and members in two sections, and the conference of Student Branch counselors. As may be seen from the schedule of events, every evening but the last is taken up with some form of entertainment and a special program of events during the days has been arranged by the women's entertainment committee. The summer convention committee has taken advantage of location and hopes to make Swampscott a gathering place for many family groups.

FREQUENCY-MODULATION DEMONSTRATION

One of the outstanding events of the convention will be the talk on frequency modulation, with demonstrations to be given by W. L. Everitt, The Ohio State University, on Wednesday evening, June 26. In addition to the demonstration of one of the most dramatic effects of frequency modulation, as announced in ELECTRICAL ENGINEERING for May, page 212, Professor Everitt will show a mechanical model which adds two sideband components to a carrier by a chain and gear arrangement. The phase of the components may be changed, and the difference between amplitude and frequency modulation for small deviation ratios shown. By a series of beat notes the large number of sideband components can be shown when the deviation ratio is large—that is, when the frequency swing is large compared with the modulating frequency.

In connection with the broadcast from the 50-kw transmitter at Paxton to show the high quality which can be obtained from a station some 50 miles away, special loudspeakers capable of reproducing the wide range will be used and the program will be selected to bring out this feature. As a high static level probably will prevail in June, the comparison with standard broadcasting should be significant.

FORMAL BANQUET AND DANCE

The climax to the entertainment program will be the formal banquet and dance, scheduled for 7:00 p.m., Thursday, June 27. The toastmaster will be Professor William H. Timbie of the Massachusetts Institute of Technology and the principal speakers will be Doctor Karl T. Compton, president, Massachusetts Institute of Technology, and Laurence A. Hawkins, executive engineer, research laboratory, General Electric Company. During the banquet Charles L. Clarke, sole surviving AIEE charter member, will be presented to the guests. There will be other special features and the sports prize awards will be presented to the winners.

INFORMATION ON WEEK-END TOURS

New England affords many opportunities for scenic and historic trips. A representative of the recreational bureau of the New England Council will be at the hotel Thursday afternoon, June 27, to assist in arranging week-end post-convention trips, as desired.

ADVANCE REGISTRATION

Members who have received an advance registration card should fill in and return the card promptly, if they have not already done so. Hotel reservations should be made directly by writing to the New Ocean House, Swampscott, Mass., or any other hotel preferred.

TECHNICAL CONFERENCES

Six technical conferences have been scheduled on the following subjects: standards, load swings, introducing modern statistical technique to electrical engineers, principles of nonlinear analysis, test codes, and dielectric measurements in the field. The scope and objectives of several of these conferences were announced in ELECTRICAL ENGINEERING for May, pages 212–13. Such additional information as has become available is announced in the following paragraphs.

Standards (*Tuesday, June 25, 2:00 p.m.*). This conference has been arranged to present the work being done by the several co-ordinating committees, and to encourage greater participation by Institute members in standards activities. The co-ordinating committees are responsible for the development of general principles and fundamental data which are common to the various standards for specific types of apparatus. The growing importance of system co-ordination, requiring that many different types of apparatus have consistent levels of dielectric strength, overload capacity, short-circuit protection, etc., makes it desirable that the various committees dealing with specific standards reach common agreement on principles.

The discussion at this conference is planned to deal especially with the methods of rating and testing apparatus for intermittent service or short-time loads. The papers by R. E. Hellmund and P. H. McAuley, V. M. Montsinger, and C. G. Veinott, scheduled for presentation at the Tuesday morning session, all deal with various aspects of this subject. It is, therefore, expected that the discussion of these papers at the morning meeting will be carried over into the afternoon conference.

Two informal topics which also deal with this subject will be presented. (1) Proposed Methods of Rating Welding Transformers, by A. U. Welch; and (2) Proposed Methods of Rating Welding Generators, by R. C. Freeman.

Following these informal talks, E. Bennett, chairman, co-ordinating committee 5, will discuss the work on basic theories and units. There also will be a general discussion of a proposed new co-ordinating committee on conduction dealing with the co-ordination of short-time and intermittent ratings of electrical apparatus and wiring.

Principles of Nonlinear Analysis (*Thursday, June 27, 2:00 p.m.*). This is intended to be the first of a series of technical conferences discussing the various methods of analysis of nonlinear problems. As an introductory meeting it will concern itself mainly with the principles of the available methods, surveying their advantages and limitations, and illustrating them with simple applications. In order to guide the general discussion, four basic methods will first be presented informally by prominent authors in the respective fields. Thus, Professor E. G. Keller, University of Texas will introduce the analytical methods with their respective limitations; A. Preisman, RCA Institutes, New York, N. Y., will demonstrate the principles of a graphical approach; Professor J. B. Scarborough, United States Naval Academy, Annapolis, Md., will illustrate numerical methods, and Professor S. H. Caldwell, Massachusetts Institute of Technology, Cambridge, will discuss the use of mechanical machines, to procure solutions of nonlinear problems.

Test Codes (*Thursday, June 27, 2:00 p.m.*). The increased variety of performance specifications required of electrical apparatus, and the great severity of requirements in regard to impulse tests, transient currents, short-circuit currents, accelerating torques, and other factors make it desirable more clearly to define test procedures on which performance guarantees are based. In many cases, different types of test may be used for different sizes of apparatus or under different conditions. It is therefore important that both designers and users of apparatus have a better understanding of the testing methods and the degrees of accuracy obtainable with different procedures. For these reasons, the various technical committees in recent years have been engaged in developing a number of different test codes.

Future AIEE Meetings

Summer Convention
Swampscott, Mass., June 24–28, 1940

Pacific Coast Convention
Los Angeles, Calif., August 27–30, 1940

Middle Eastern District Meeting
Cincinnati, Ohio, October 9–11, 1940

Winter Convention
Philadelphia, Pa., January 27–31, 1941

At this conference, it is proposed to discuss two new test codes which are now approaching completion, and also to consider revisions in one of the existing codes. The two new test codes to be presented are the test code for single-phase motors and the test code for d-c machines. The third code to be discussed is that for polyphase induction machines.

It has been proposed that material common to several codes, such as methods of measuring temperature, resistance, and dielectric strength, be segregated and placed in a separate code. This proposal has been under consideration by the instruments and measurements committee and will be discussed at this conference.

Dielectric Measurements in the Field (*Thursday, June 27, 2:00 p.m.*). This conference is sponsored by a subcommittee of the committee on instruments and measure-

Technical Program

(Eastern Daylight Saving Time)

Photo-offset copies of authors' manuscripts, except addresses, may be obtained as soon as available in advance of the convention by writing to the AIEE order department, 33 West 39th Street, New York, N. Y. Only numbered papers will be available in advance-copy form. If ordered by mail, price 10 cents per copy; if purchased at Institute headquarters or at the convention, 5 cents per copy. Mail orders (particularly from out-of-town members) are advisable, inasmuch as an adequate supply of each paper at the meeting cannot be assured. Coupon books in $1 and $5 denominations are available for those who wish to avoid remittance by check or otherwise. Most of the papers ultimately will be published in ELECTRICAL ENGINEERING or the TRANSACTIONS.

Tuesday, June 25

9:00 a.m. Power Transmission

40-107. Shielding of Transmission Lines. **C. F. Wagner, G. D. McCann,** and **G. L. MacLane, Jr.,** Westinghouse Electric and Manufacturing Company

40-105. Abnormal Voltage Conditions in Three-Phase Systems Produced by Single-Phase Switching. **Edith Clarke, H. A. Peterson,** and **P. H. Light,** General Electric Company

40-106. Arcing Faults in Power Systems. **C. Concordia** and **H. A. Peterson,** General Electric Company

9:00 a.m. Standards

40-94. Rating of Potential Devices and Suggested Standards. **J. E. Clem,** General Electric Company, and **P. O. Langguth,** Westinghouse Electric and Manufacturing Company

40-95. Some Problems in the Standardization of Temperature Ratings of Fractional Horsepower Motors. **C. G. Veinott,** Westinghouse Electric and Manufacturing Company

40-93. A Study of Short-Time Ratings and Their Application to Intermittent Duty Cycles. **R. E. Hellmund** and **P. H. McAuley,** Westinghouse Electric and Manufacturing Company

40-96. Effect of Load Factor on Operation of Power Transformers by Temperature. **V. M. Montsinger,** General Electric Company

40-92. Reference Values for Temperature, Pressure, and Humidity. **P. L. Bellaschi** and **P. H. McAuley,** Westinghouse Electric and Manufacturing Company

9:00 a.m. Basic Sciences

40-108. Transient Analysis of Completely Transposed Multiconductor Transmission Lines. **L. A. Pipes,** Harvard University

40-109. Linear Transformations in Three-Phase Circuits. **L. A. Pipes,** Harvard University

40-110. Some Characteristics and Applications of Negative Glow Lamps. **H. M. Ferree,** General Electric Company

9:00 a.m. Electronics

40-111. A Decade of Progress in Electronic Means of Communication. Report of Subcommittee on Electronics, prepared by **S. B. Ingram,** Bell Telephone Laboratories, Inc.

40-112. A Decade of Progress in the Use of Electronic Tubes in Other Than the Communication Field. Report of Subcommittee on Electronics, prepared by **W. C. White,** General Electric Company

40-113. Measurements at Radio Frequencies. **H. P. Meahl, P. C. Michel, M. W. Scheldorf,** and **T. M. Dickinson,** General Electric Company

Wednesday, June 26

9:00 a.m. Communication

40-116. Frequency Modulation. **W. L. Everitt,** The Ohio State University

40-117. Aircraft Storm-Static Radio Interference. **E. C. Starr,** Oregon State College

40-118. High-Voltage Direct-Current Point Discharges. **E. C. Starr,** Oregon State College

40-119. A Wide-Band Square-Wave Generator. **E. H. B. Bartelink,** General Electric Company

9:00 a.m. Testing of Insulation and Cables

40-81. Low-Voltage D-C Measurements on Electrical Insulating Oils. **J. L. Oncley** and **W. C. Hollibaugh,** Massachusetts Institute of Technology

40-82. Rapid Recording A-C Bridge. **W. Mikelson** and **H. W. Bousman,** General Electric Company

40-84. A Method for Detecting the Ionization Point on Electrical Apparatus. **G. E. Quinn,** Consolidated Edison Company of New York, Inc.

40-121. The Type CB Impregnated-Paper Cable. **S. J. Rosch,** Anaconda Wire and Cable Company

40-104. The Dielectric Strength and Life of Impregnated Paper Insulation—II: The Influence of the Thickness of the Paper. **J. B. Whitehead,** The Johns Hopkins University

9:00 a.m. Transportation

40-122. Modern Rail Transport. **A. M. Wright,** The Central Railroad Company of New Jersey

40-123. The Application of Electricity for the Auxiliaries of Railroad Trains. **J. E. Gardner,** Chicago, Burlington, and Quincy Railroad Company

40-124. Investigation of Starting Requirements for Alco 660-Horsepower Diesel Engine. **J. C. Davidson** and **R. Lamborn,** General Electric Company

Thursday, June 27

10:00 a.m. General Session

Friday, June 28

9:00 a.m. Protective Devices

40-103. A High-Speed Differential Relay for Generator Protection. **W. K. Sonnemann,** Westinghouse Electric and Manufacturing Company

40-87. Harmonic-Current-Restrained Relays for Transformer Differential Protection. **C. D. Hayward,** General Electric Company

40-85. A High-Power Oilless Circuit Interrupter Using Water. **W. M. Leeds,** Westinghouse Electric and Manufacturing Company

40-125. Medium-Capacity Air-Blast Circuit Breakers for Metal-Clad Switchgear. **R. M. Bennett** and **B. W. Wyman,** General Electric Company

40-86. Dielectric Strength of Water in Relation to Use in Circuit Interrupters. **Joseph Slepian, C. L. Denault,** and **A. P. Strom,** Westinghouse Electric and Manufacturing Company

9:00 a.m. Instruments and Measurements

40-88. An Improved Type of Direct-Current Wattmeter of the Shunted Type. **Paul MacGahan,** Westinghouse Electric and Manufacturing Company

40-89. Computation of Accuracy of Current Transformers. **A. T. Sinks,** General Electric Company

40-90. New Instruments for Recording Lightning Currents. **C. F. Wagner** and **G. D. McCann,** Westinghouse Electric and Manufacturing Company

40-91. The Output and Optimum Design of Permanent Magnets Subjected to Demagnetizing Forces. **A. J. Hornfeck,** Bailey Meter Company, and **R. F. Edgar,** General Electric Company

40-97. A New High-Speed Thermal Wattmeter. **John H. Miller,** Weston Electrical Instrument Corporation

9:00 a.m. Electrical Machinery

40-98. An Extension of the Method of Symmetrical Components Using Ladder Networks. **W. V. Lyon,** Massachusetts Institute of Technology

40-99. Effective Resistance to Alternating Currents of Multilayered Windings. **Edward Bennett,** University of Wisconsin, and **Sidney C. Larson,** General Electric X-Ray Corporation

40-100. Transient Starting Torques in Induction Motors. **A. M. Wahl** and **L. A. Kilgore,** Westinghouse Electric and Manufacturing Company

40-101. Dead Points in Squirrel-Cage Motors. **Quentin Graham,** Westinghouse Electric and Manufacturing Company

40-102. Performance of Traveling Waves in Coils and Windings. **R. Rudenberg,** Harvard University

ments. It will cover the various types of testing equipment and test methods used to determine the quality of insulation of electrical apparatus in service. A number of prepared discussions will be presented, and it is hoped that additional discussion will be contributed by any who desire to attend. In this way it is believed that the subject will be clarified and the publication of future papers will be encouraged.

A schedule of convention events was published in the May issue, page 212.

COLONEL ROBERT S. HENRY TO ADDRESS JOINT GENERAL SESSION

Feature of the general session, which is being held jointly with the American Engineering Council, Thursday, June 27, at 10 a.m., will be an address on "Transportation as a Social Problem", by Colonel Robert Selph Henry, assistant to the president, Association of American Railroads.

Widely known as a colorful and highly qualified speaker, Colonel Henry has been intimately associated with American railroading since 1921. He was born in Clifton, Tenn., in 1889, and educated in Nashville, Tenn., receiving the degrees of bachelor of laws (1910) and bachelor of arts (1911) from Vanderbilt University. He was admitted to the Tennessee bar in 1911, and after working as a newspaper reporter and serving as private secretary to the governor of Tennessee, he began the practice of law in Nashville in 1915.

Colonel Henry is the author of several books on trains and rail transportation: "Trains", "On the Railroad", and "Portraits of the Iron Horse". He has also published two books on Confederate history, a subject in which he became interested as a hobby and on which he now is regarded as an authority.

1940 Lamme Medal Nominations Due December 1

Special attention is directed to the fact that the names of Institute members who are considered eligible for the AIEE Lamme Medal, to be awarded early in 1940, may be submitted by any member in accordance with section 1 of article VI of the bylaws of the Lamme Medal committee, as quoted in the following:

> The committee shall cause to be published in one or more issues of ELECTRICAL ENGINEERING, or of its successors, each year, preferably including the June issue, a statement regarding the "Lamme Medal" and an invitation for any member to present to the national secretary of the Institute by December 1, the name of a member as a nominee for the medal, accompanied by a statement of his "meritorious achievement" and the names of at least three engineers, of standing who are familiar with the achievement.

Each nomination should give concisely the specific grounds upon which the award is proposed, and also a complete detailed statement of the achievements of the nominee to enable the committee to determine its significance as compared with the achievements of other nominees. If the work of the nominee has been of a somewhat general character in co-operation with others, specific information should be given regarding his individual contributions. Names of endorsers should be given as specified in the foregoing quotation.

Section and Branch Activities

Annual Report for 1939–40

THE following constitutes the annual report on Institute Section and Branch activities for the fiscal year which ended April 30, 1940. Similar information for three preceding fiscal years appeared in ELECTRICAL ENGINEERING for June 1939, pages 268–71; June 1938, pages 263–6; June 1937, pages 762–5.

Present members of the Sections committee and the committee on Student Branches, which supervise the two important divisions of Institute activities covered by this report, are:

Sections—H. H. Race, *chairman*, M. S. Coover, C. A. Faust, O. W. Holden, E. T. Mahood, I. M. Stein, J. M. Thomson, W. H. Timbie, and *ex-officio*, the chairmen of all Sections of the Institute.

Student Branches—R. W. Sorensen, *chairman*, C. T. Almquist, S. S. Attwood, H. W. Bibber, W. C. DuVall, E. A. Loew, C. W. Ricker, Charles F. Scott, E. M. Strong, and *ex-officio*, all Student Branch counselors.

SECTION ACTIVITIES

Three new Sections were organized: Charleston (W. Va.), El Paso, and South Carolina. On account of their extensive territories, the names of two Sections were changed: Baltimore to "Maryland" and Dallas to "North Texas". The territory of the North Texas Section was extended to include some unassigned counties to the north and northwest. The nine unassigned counties in Maine were assigned to the Lynn Section, which now has the entire state.

All Sections reported activity during the year, and the total number of meetings reported was 701, as compared with 635 for the preceding year. This was the sixth consecutive fiscal year in which the number was larger than for any preceding year. Nine Sections held more than 15 meetings each, 7 held from 12 to 15, 36 held from 8 to 11, 10 held from 4 to 7, and only 8, including 3 recently organized, held fewer than 4 meetings each.

Fifteen Sections reported meetings by a total of 30 technical groups or other subdivisions, with a total of 124 meetings of these types, in addition to 131 regular Section meetings.

The number of members in the United States outside of Section territories was reduced in 1937, by revision of many of the territories, to about 200. The formation of new Sections and some further revisions in territories have reduced this number to 101 as of February 29, 1940. These are located in 50 cities and towns in 11 states, with the maximum numbers of 11 in one city, and 23 in one state.

In October 1939, the Sections committee issued a printed pamphlet entitled "Section Activities", containing in condensed form information on the aims and activities of the Sections collected during the preceding three years, and intended to assist Section officers in their efforts to become acquainted with the types of activities which have been found to be most fruitful. Under the joint direction of the Sections committee and the committee on Student Branches, copy for a second edition of the pamphlet "The Electrical Engineer" was prepared. Distribution of printed copies was begun in March.

The Sections committee recommended to the Sections that each appoint committees on (*a*) legislation, (*b*) economic and social affairs, and (*c*) vocational guidance.

During the past year, the Sections committee has developed a comprehensive plan for the preparation by one of its members of news items on outstanding Section activities for publication in ELECTRICAL ENGINEERING, and many have appeared.

The Sections committee is making a comprehensive study of all phases of Section activities through a detailed questionnaire sent out in two parts in March and April.

In addition to officers of the Institute, E. H. Armstrong, P. A. Borden, F. A. Cowan, W. A. Gluesing, R. J. Kryter, Everett S. Lee, A. C. Monteith, J. O. Perrine, M. E. Strieby, C. F. Wagner, and W. E. Wickenden each gave addresses at meetings of 3 or more Sections, the larger numbers being 20 for Mr. Wagner, and 8 for Doctor Perrine.

The interest of the Sections in increasing the participation by the younger members in their activities has advanced rapidly, as shown by the outstanding success of the technical group discussion plan, the appointment of committees on younger engineers, and the growing practice of including some of the younger men among the regular Section officers and committees.

The first joint meeting of the Chicago Section and the Student Branches at Northwestern University and Armour and Lewis Institutes was held at Northwestern University in March. The Section sponsored a paper-writing contest for students, with arrangements that each of the three Branches should conduct a contest and submit its two best papers to the judges appointed by the Section, and that the two best papers selected by them should be presented in final competition at the joint meeting. Prizes of $20 and $10 were awarded. The student papers were followed by an address on "The Engineers' Job", by Alex D. Bailey, chief operating engineer, Commonwealth Edison Company. The Section hopes to have such a meeting annually.

Some of the Sections which have recently established committees on activities for the younger members are: Chicago, Cincinnati, Maryland, and Washington. The Maryland Section's discussion committee, composed of younger men, promotes interest among the younger members, and arranges for a brief talk, preferably by a younger member, preceding each main lecture. The Washington Section began holding junior technical sessions.

The Maryland Section held its first paper-writing contest for students, with an engraved sterling-silver goblet and an engraved sterling-silver key chain as prizes. The two winning papers were presented at a joint meeting with the Johns Hopkins University Branch. The Section has also begun holding weekly luncheon meetings with attendance from 12 to 20.

The Los Angeles Section followed its custom of many years standing by celebrating its past chairmens' night. All past

chairmen were invited to the dinner meeting as guests of the Section, and of the 25 living 21 attended. One of them was appointed toastmaster, and each was introduced and given an opportunity to speak.

The Lynn Section held a question-and-answer meeting at which certain electrical engineers answered questions on electrical subjects which they had not seen in advance. Prizes were offered for any such questions which they were unable to answer.

In the Lynn Section's technical-paper competition for its members under 35 years of age, 20 papers were submitted, 8 were presented at its local convention on March 26, and prizes of $15, $10, and $5 were awarded.

The Madison Section authorized the formation of a Rock River Valley subsection with headquarters in Rockford, Ill., and also including members in Beloit, Wis., and Freeport, Ill.

The Michigan Section has been conducting for several years round-table discussions on specialized technical subjects. The freedom of discussion and increasing interest in these have been noticeable during the past year.

The Michigan Section continued its co-operation with the Engineering Society of Detroit in the holding of an annual meeting for high-school seniors interested in engineering. The meeting held in December 1939 was attended by more than 300 seniors, and was considered highly successful.

The Milwaukee Section distributed to its members on March 6 a questionnaire regarding the desirability of organizing technical discussion groups, requesting information as to what divisions of electrical engineering are of greatest interest.

The power group of the New York Section has continued its practices of holding a prize paper contest and providing several educational courses on subjects of keen interest to many members, and the communication group provided a series of six lectures on modern methods for communication measurements. It has been holding occasional

Table I. Section Meetings Held During Year Ending April 30, 1940

Section	AIEE Members August 1938	AIEE Members August 1939	Meetings During Year Number	Meetings During Year Average Attendance	Average Attendance as Per Cent of Membership, August 1939
Akron	76	75	8	65	87
Alabama	39	31	3	18	58
Boston	411	414	9	225	54
Central Indiana	123	126	6	119	94
Charleston, W. Va.*			1	22	
Chicago	697	733	5	294	40
Industrial group			3	89	
Power group			4	108	
Communication group			4	433	
Cincinnati	182	180	10	219	122
Cleveland	300	298	10	225	75
Technical group			6	64	
Columbus	87	95	7	43	45
Connecticut	267	265	10	95	36
Denver	168	182	8	73	40
East Tennessee	102	118	11	98	83
El Paso**			2	25	
Erie	67	65	9	123	189
Florida	68	73	3	121	166
Fort Wayne	88	98	11	168	171
Georgia	97	104	12	115	111
Houston	116	139	8	89	64
Iowa	50	67	7	26	39
Ithaca	47	51	10	55	108
Kansas City	124	125	9	108	86
Lehigh Valley	193	191	7	91	48
Los Angeles	486	483	10	175	36
Louisville	50	56	7	92	164
Lynn	130	145	4	800	552
Inspection trips			4	78	
Technical lectures			5	355	
Local conventions			2	175	
Madison	64	65	6	61	94
Rock River Valley Subsection			3	42	
Mansfield		64	8	223	348
Maryland	201	224	11	131	58
Memphis	53	61	11	60	98
Mexico	66	56	1	27	48
Michigan	342	358	9	189	53
Round table discussions			4	19	
Milwaukee	297	270	13	170	63
Minnesota	83	89	5	73	82
Power group			1	52	
Montana	39	39	2		
Muscle Shoals	40	46	8	22	48
Nebraska	58	56	6	237	423
New Orleans	78	97	7	79	81
New York	3,346	3,355	5	380	11
Communication group			5	189	
Basic science group			3	160	
Power group			11	143	
Illumination group			3	517	
Transportation group			2	150	
Niagara Frontier	205	201	9	219	109
North Carolina	78	85	2	88	104
North Texas	114	140	10	112	80
Oklahoma City	106	120	11	128	107
Philadelphia	580	610	9	158	26
Power systems group			3		
Industrial practice group			3		
Communication group			4		
Pittsburgh	503	517	8	236	46
Pittsfield	167	178	6	1,013	569
Technical meetings			5	217	
Colloquium meetings			5	21	
Portland	125	151	9	91	60
Communication committee			5	41	
Transmission and distribution committee			6	99	
Providence	95	91	8	204	224
Rochester	94	95	10	161	169
Communication group			1	76	
Luncheon meetings			4	25	
St. Louis	247	268	10	109	41
San Antonio	37	43	8	52	121
San Diego		30	8	84	280
San Francisco	457	486	10	146	30
Technical meetings			7	79	
Saskatchewan	25	21	11	35	167
Schenectady	428	403	8	213	53
Technical discussion meetings			4	119	
Open forum series			6	20	
Seattle	156	153	10	106	69
Technical meetings			4	56	
Sharon	80	86	10	96	112
South Carolina†			2	37	
Spokane	62	62	8	61	98
Springfield	57	60	8	160	267
Syracuse	73	71	25	146	206
Toledo	78	78	10	85	109
Toronto	348	338	8	169	50
Discussion group			6	82	
Tulsa	88	107	9	104	97
Urbana	65	77	8	187	243
Utah	56	76	7	47	62
Vancouver	98	107	10	54	50
Virginia	92	94	4	67	71
Washington	288	332	11	133	40
Technical sessions			9	120	
Junior technical sessions			2	55	
Wichita	33	46	11	41	89
Worcester	69	58	9	91	157
Total....70	13,539	14,078			

Total number of meetings.............. 701

Total attendance.............................91,949

*Organized April 9, 1940. **Organized March 7, 1940. †Organized March 2, 1940.

Table II. Section Meetings Held During Last Three Fiscal Years

	Fiscal Year Ending April 30 1938	1939	1940
Number of Sections	65	67	70
Number of meetings held	624	635	701
Average number of meetings	9.6	9.5	10.0
Total attendance	110,148	85,692	91,949
Average attendance per meeting	177	135	131

Table III. Prizes Awarded by Sections

Section	Number of Papers Presented	Awards
Central Indiana	3	$5, $3, $2
Chicago	2	$20, $10
Cincinnati	6	$10, $5
Houston	4	$15, $10, $5
Iowa	6	Two Standard Handbooks
Kansas City	4	$15, $10, $5, pocket slide rule
Los Angeles	4	$15
Maryland	3	Silver goblet, two silver key chains
Minnesota	4	$15, $10, $5, $5
New Orleans	3	Two Associate membership prizes
New York	7	$25, $10
Pittsfield*	8	$15, $10
Portland	3	One year Associate dues
St. Louis	6	$15, $10, $5
Schenectady*	6	$15, $10
Toronto	4	Two prizes
Urbana	4	$5, $3, $2
Utah	3	One year Associate dues
Worcester	5	$10, $5

* Two meetings in competition between Sections.

Table IV. Branch Meetings Held During Year Ending April 30, 1940

Branch	Meetings During Year: Number	Average Attendance	Approximate Number of Talks by Students
Akron, University of	10	24	1
Alabama Polytechnic Institute	14	41	5
Alabama, University of	11	19	9
Alberta, University of*	7	23	5
Arizona, University of	27	12	22
Arkansas, University of	11	21	3
Armour Institute of Technology	8	52	2
British Columbia, University of	10	19	16
Brooklyn, Polytechnic Institute of			
Day division	1	55	
Evening division	7	22	4
Brown University	4	14	
Bucknell University	13	21	1
California Institute of Technology	17	31	4
California, University of	27	35	15
Carnegie Institute of Technology	29	56	23
Case School of Applied Science	24	51	23
Catholic University of America	2	12	
Cincinnati, University of	10	158	7
Clarkson College of Technology	9	40	
Clemson Agricultural College			
Colorado State Agricultural College	6	105	3
Colorado, University of	8	60	5
Columbia University	1	23	
Cooper Union			
Day division	8	20	2
Evening division	7	19	5
Cornell University	5	60	
Denver, University of	6	53	
Detroit, University of	9	51	
Drexel Institute	13	24	4
Duke University	12	20	1
Florida, University of	6	29	1
George Washington University	9	32	2
Georgia School of Technology	9	53	
Harvard University	3	84	
Idaho, University of	17	39	4
Illinois, University of	10	630	4
Iowa State College	5	102	2
Iowa, University of	12	34	9
Johns Hopkins University	18	23	14
Kansas State College	9	130	13
Kansas, University of	9	38	2
Kentucky, University of	24	58	2
Lafayette College	12	12	6
Lehigh University	5	71	3
Lewis Institute	15	26	
Louisiana State University	16	21	4
Louisville, University of	8	20	4
Maine, University of	11	21	3
Marquette University	6	20	
Maryland, University of	7	26	4
Massachusetts Institute of Technology	10	67	
Michigan College of Mining and Technology	9	578	
Michigan State College	13	27	
Michigan, University of	10	52	
Milwaukee School of Engineering	9	48	
Minnesota, University of	11	70	4
Mississippi State College	3	41	
Missouri School of Mines and Metallurgy	10	32	7
Missouri, University of	7	40	3
Montana State College	35	49	129
Nebraska, University of	17	116	6
Nevada, University of	13	24	3
Newark College of Engineering	10	35	7
New Hampshire, University of	18	22	9
New Mexico State College	14	19	7
New Mexico, University of	9	14	10
New York, College of the City of			
Day division	30	51	4
Evening division			
New York University			
Day division	5	28	
Evening division	6	20	1
North Carolina State College	15	50	2
North Dakota State College	6	18	2
North Dakota, University of	11	14	4
Northeastern University	20	55	7
Northwestern University	5	42	
Notre Dame, University of	11	35	3
Ohio Northern University	15	37	7
Ohio State University	12	38	9
Ohio University	7	23	
Oklahoma A. & M. College	12	228	7
Oklahoma, University of	12	72	5
Oregon State College	13	61	9
Pennsylvania State College	9	43	
Pennsylvania, University of	3	24	
Pittsburgh, University of	25	100	18
Puerto Rico, University of	6		2
Pratt Institute	22	45	5
Princeton University	5	14	4
Purdue University	15	69	
Rensselaer Polytechnic Institute	7	166	12
Rhode Island State College	18	24	
Rice Institute	12	16	2
Rose Polytechnic Institute	4	71	2
Rutgers University	7	34	2
Santa Clara, University of	14	11	11
South Carolina, University of	4	24	
South Dakota State College	12	21	4
South Dakota State School of Mines	10	19	
Southern California, University of	13	45	11
Southern Methodist University	3	16	1
Stanford University	8	23	
Stevens Institute of Technology			
Swarthmore College	9	24	2
Syracuse University	19	22	19
Tennessee, University of	10	28	
Texas A. & M. College	10	44	4
Texas Technological College	15	24	4
Texas, University of	7	72	6
Tufts College	6	53	6
Tulane University	9	25	3
Union College	3	27	
Utah, University of	5	30	3
Vermont, University of	8	25	5
Villanova College	15	15	4
Virginia Military Institute	13	45	6
Virginia Polytechnic Institute	20	66	12
Virginia, University of	9	21	3
Washington, State College of	19	46	7
Washington, University of	11	61	8
Washington University	11	23	
West Virginia University	19	25	102
Wisconsin, University of	7	54	5
Worcester Polytechnic Institute	7	61	9
Wyoming, University of	9	12	3
Yale University	3	27	
Total......121			767

Total number of meetings............ 1,346
Total attendance....................64,972

* Authorized by board of directors, May 26, 1939.

round-table meetings to provide opportunities for informal discussions among members in similar fields of work.

The Oklahoma City Section devoted one of its meetings to the presentation of papers by four of its members, with a time allotment of about 25 minutes each. The Tulsa Section had a similar type of meeting with each of four speakers limited to about 15 minutes.

The Philadelphia Section has established three discussion groups: communication, industrial practice, and power systems, which are holding a total of 10 meetings per year with excellent attendance. Plans are under way for the formation of a discussion group on instruments and measurements. During the past year, informal weekly luncheons have been held with a weekly drawing for a free lunch; average attendance 22.

Table V. Branch Meetings Held During Last Three Fiscal Years

	Fiscal Year Ending April 30: 1938	1939	1940
Number of Branches	120	120	121
Number of meetings held	1,334	1,190	1,346
Average number of meetings	11.1	9.9	11.1
Total attendance	60,446	53,380	64,972
Average attendance per meeting	45.3	44.8	48.3
Number of student talks	897	725	767

The Schenectady Section and three other organizations sponsored a technical discussion series, and an open forum series of six meetings with addresses by the heads of six divisions of the city government.

Tables I, II, and III contain detailed information on Section activities. Table VI presents a comprehensive record of co-operation between Sections and Branches, with 26 Sections and 39 Branches participating, as compared with 20 Sections and 30 Branches for the preceding year.

STUDENT ACTIVITIES

The organization of the University of Alberta Branch in May 1939 brought the total number to 121.

Only two Branches failed to report any activity during the year. The total number of meetings was 1,346, as compared with 1,190 for the preceding year, 1,334 for 1937–38, and 1,363 for 1936–37. Twenty-one Branches held more than 15 meetings each, 24 held from 12 to 15, 40 held from 8 to 11, 26 held from 4 to 7, and only 10 held fewer than 4 meetings.

The total number of talks by students was 767, a slight increase over the 725 for the preceding year, but far below the totals for some previous years. This fundamentally important phase of Branch work offers the greatest opportunity for improvement in the activities.

Of 1,624 Enrolled Students whose terms, according to Institute records, were expected to expire on April 30, 911 or about 56 per cent applied for admission as Associates. The corresponding records for the preceding year were 1,564, 849, and 54 per cent.

The committee on Student Branches

Table VI. Section or Joint Section and Branch Meetings With Active Student Participation

Sections	Schools	Date	Student Talks	Attendance
San Antonio	University of Texas	5/1/39	4	31
New Orleans	Louisiana State University Tulane University	5/5/39	3	110
North Carolina	North Carolina State College	5/5/39	1	74
Los Angeles	California Institute of Technology University of Southern California	5/9/39	4	99
Cincinnati	University of Cincinnati	5/11/39	6	110
Oklahoma City	University of Oklahoma	5/18/39	2	146
St. Louis	Missouri School of Mines and Metallurgy University of Missouri Washington University	5/19/39	6	100
Portland	Oregon State College	5/20/39	3	78
Utah	University of Utah	5/22/39	3	36
Madison	University of Wisconsin	5/23/39	4	50
Worcester	Worcester Polytechnic Institute	5/24/39	5	80
Toronto	University of Toronto	12/8/39	4	67
San Antonio	University of Texas	12/14/39	1	75
Pittsburgh	Carnegie Institute of Technology Pennsylvania State College University of Pittsburgh West Virginia University	1/9/40	4	266
Vancouver	University of British Columbia	2/26/40	4	51
Kansas City	University of Kansas	3/7/40	4	170
Akron	University of Akron	3/12/40	1	76
Houston	Rice Institute Texas A. & M. College	3/15/40	4	80
North Texas	Southern Methodist University	3/25/30	3	68
Chicago	Armour Institute of Technology Lewis Institute Northwestern University	3/28/40	2	125
Urbana	University of Illinois	4/4/40	4	35
Central Indiana	University of Illinois Purdue University Rose Polytechnic Institute	4/6/40	3	187
Los Angeles	California Institute of Technology University of Southern California	4/9/40	5	300
New Orleans	Louisiana State University Tulane University	4/15/40	2	
Minnesota	University of Minnesota	4/22/40	4	100
El Paso	New Mexico State College	4/25/40	2	19
Iowa	Iowa State College University of Iowa	4/25/40	6	62
New York and District 3	College of the City of New York Columbia University Cooper Union Newark College of Engineering New York University Polytechnic Institute of Brooklyn Pratt Institute Rutgers University Stevens Institute of Technology	4/25/40	7	400
Spokane	University of Idaho State College of Washington	4/26/40	2	119
Maryland	Johns Hopkins University	4/29/40	3	90
Totals—26 Sections, 39 Branches			106	3,204

Table VII. Conferences on Student Activities

District	Location	Date
1	Springfield, Mass. (North Eastern District meeting)	5/3–5/39
8 and 9, University of British Columbia	San Francisco, Calif. (Pacific Coast convention)	6/26–30/39
5	Minneapolis, Minn. (Great Lakes District meeting)	9/18/39
2	Scranton, Pa. (Middle Eastern District meeting)	10/11–13/39
4	Mississippi State College, State College	4/13/40
6	University of North Dakota, Grand Forks	4/19–20/40
7	Texas Technological College, Lubbock	4/19–20/40

Table VIII. Student Conventions

Sponsor (District, Section, or Branch)	Location	Date	Number of Student Papers
1	Springfield, Mass. (North Eastern District meeting)	5/3–5/39	15
8 and 9, University of British Columbia	San Francisco, Calif. (Pacific Coast convention)	6/26–30/39	11
5	Minneapolis, Minn. (Great Lakes District meeting)	9/18/39	13
4	Mississippi State College, State College	4/11–13/40	6
6	University of North Dakota, Grand Forks	4/19–20/40	9
7	Texas Technological College, Lubbock	4/19–20/40	
2	Swarthmore College, Swarthmore, Pa.	4/22/40	5
3 and New York Section	Pratt Institute, Brooklyn, N. Y.	4/25/40	7

urged that each Branch celebrate in some appropriate manner the 75th birthday of Doctor Charles F. Scott, originator of the plan for organizing Student Branches. A Charles F. Scott jubilee committee was organized with A. C. Stevens as chairman. The committee had a motion-picture film of Professor Scott prepared, and this and the film taken several years ago in the "past-presidents series" were made available to the Branches. They were shown at about 75 Branch meetings, many of which were joint meetings with other Branches and Sections.

The committee appointed in January 1939 to prepare copy for a second edition of the pamphlet "The Electrical Engineer," representing the Sections committee and the committee on Student Branches, distributed 188 copies of a revised manuscript to educators and others interested for comment. The 61 replies received were studied and the suggestions incorporated in so far as seemed advisable. Distribution of single copies in printed form was made about March 15 to Sections, Branches, and a large number of high schools. Up to April 30, orders had been received for 2,109 additional copies.

The committee on safety again suggested that each Branch have a meeting devoted to prevention of accidents or remedial measures after electric shocks. Many Branches carried out the suggestion.

Student technical sessions in connection with regular Institute meetings were held as follows: North Eastern District meeting, Springfield, Mass., May 3–5, two parallel sessions, 15 papers, two prizes at each session; summer-Pacific Coast convention, San Francisco, Calif., June 26–30, two sessions, 11 papers; Great Lakes District meeting, Minneapolis, Minn., September 27–29, one session, 13 papers.

The College of the City of New York held a smoker in February in the form of an inter-Branch get-together to encourage acquaintance and correlation of activities among the Branches in the city and vicinity. In the attendance of more than 100, seven Branches were represented, with a total of 40 from the visiting Branches.

The Branches in the Middle Eastern District have co-operated in the preparation and distribution of a mimeographed news sheet on their activities.

Tables IV and V contain information on Branch meetings. Table VI gives a record of co-operation between Sections and Branches, showing participation by 26 Sections and 39 Branches, as compared with 20 Sections and 30 Branches for the preceding year. Tables VII and VIII present summarized data on student conferences and conventions.

National • • • •

Pacific Coast Convention to Be Held in Los Angeles

Arrangements for the 1940 AIEE Pacific Coast convention, which will be held in Los Angeles, Calif., August 27–30, are now practically complete, according to N. B. Hinson, general chairman. The Ambassador Hotel, famous for its Cocoanut Grove, has been chosen for the convention headquarters. The dates are an ideal time for members throughout the country to plan their vacation trips. For women guests shopping, sightseeing tours, and other events of interest will be arranged.

The opening session will be addressed by Professor R. W. Sorensen, nominee for AIEE president for 1940–41, and the principal speaker will be Douglas Shearer, sound director of Metro-Goldwyn-Mayer Studios, who will discuss many interesting phases of motion-picture production.

The tentative technical program is comprised of five sessions and one conference on governors and frequency control. Technical sessions are on the following subjects: protective devices; instruments, measurements, and basic sciences; power transmission and distribution; electrical machinery; and a joint session with the Institute of Radio Engineers on communication and related subjects. The protective-devices session is expected to be outstanding, as there will be several papers presented on new design of circuit breakers and new relay applications. Present indications are that the sessions will be unique, in that every paper will be presented by the author. In addition, there will be student sessions and a student and counselor dinner and conference.

There are many points of interest in and around Los Angeles available for inspection trips, such as the 200-inch telescope at Mt. Palomar, 100-inch telescope at Mt. Wilson, Boulder Dam, NBC and Columbia broadcasting studios, Metropolitan Aqueduct, new receiving stations for Boulder Dam power, the Griffith Park Planetarium, and others.

Special emphasis is being placed on sports—tennis, golf, swimming, and others. The annual play for the Fisken golf cup will take place at The Riviera Country Club.

National Prize Awards for 1939 Papers Announced

The AIEE committee on the award of Institute prizes, after considering all eligible papers, has announced the national prize awards for papers presented during 1939. On all except Branch papers the committee had the benefit of recommendations from the chairmen of technical committees on papers in their respective fields. No award is being made for best paper in public relations and education, since no eligible papers were presented during 1939. The prizes will be presented at the annual meeting of the Institute, June 24, 1940, during the forthcoming summer convention at Swampscott, Mass. The committee consists of J. W. Barker, *chairman,* W. S. Davidson, H. S. Osborne, I. Melville Stein.

Papers and authors receiving awards in the various classifications are:

Best Paper in Engineering Practice: Prize was awarded to F. J. Scudder (M'25) and John N. Reynolds, Bell Telephone Laboratories, for their paper on "Crossbar Dial Telephone Switching System", presented at the winter convention, January 23–27, 1939, and published in the 1939 TRANSACTIONS (May section) pages 179–92. Honorable mention was made of the paper on "Pennsylvania Railroad, New York-Washington-Harrisburg Electrification, Relay Protection of Power Supply System", by E. L. Harder (A'30) Westinghouse Electric and Manufacturing Company, presented at the 1939 winter convention, and published in the 1939 TRANSACTIONS (June section) pages 266–73; and of the paper "A 12-Channel Carrier Telephone System for Open-Wire Lines", by B. W. Kendall (M'18, F'29) and H. A. Affel (A'18, M'23) Bell Telephone Laboratories, presented at the 1939 winter convention and published in the 1939 TRANSACTIONS (July section) pages 351–60.

Best Paper in Theory and Research: Prize was awarded to F. C. Holtz (A'16, M'29) Sangamo Electric Company, for his paper on "The Anomalous Behavior of the Moving Systems of Single-Phase A-C Watt-Hour Meters at No Load", presented at the combined summer and Pacific Coast convention, San Francisco, Calif., June 26–30, 1939, and published in the TRANSACTIONS section of ELECTRICAL ENGINEERING, February 1940, pages 116–21. Honorable mention was made of the paper "Subharmonics in Circuits Containing Iron-Cored Inductors—II", by Irven Travis (A'32) University of Pennsylvania, presented at the 1939 winter convention and published in the 1939 TRANSACTIONS, pages 735–42; and of the paper "A New Time Standard" by H. E. Warren (A'02) Warren Telechron Company, presented at the 1939 summer and Pacific Coast convention and published in the TRANSACTIONS section of ELECTRICAL ENGINEERING, March 1940, pages 137–41.

Initial Paper: Prize was awarded to W. C. Johnson (A'35) Princeton University, for his paper on "Predetermination of Temperatures in Resistance Welds", presented at the 1939 winter convention and published in the 1939 TRANSACTIONS, pages 845–53. Honorable mention was made of the paper "Breakdown Studies in Compressed Gases" by A. H. Howell (A'35), Massachusetts Institute of Technology, presented at the 1939 winter convention and published in the 1939 TRANSACTIONS (May section) pages 193–204; and of the paper "Signal System, Interlocking Plants, and Automatic Train Control on the San Francisco-Oakland Bay Bridge Railway" by C. R. Davis A'36) California State Public Works Department, presented at the 1939 summer and Pacific Coast convention and published in the TRANSACTIONS section of ELECTRICAL ENGINEERING, March 1940, pages 158–64.

Branch Paper: The prize was awarded jointly to W. N. Brown, Jr., and E. W. Sheridan, Massachusetts Institute of Technology, for their paper on "Frequency-Selective Feedback for Improvement of Acoustical Response of an Audio-Frequency Sound System" and to E. C. Dench, Worcester Polytechnic Institute, for his paper on "The 'Glo-Relay', a New Method of Initiating Vapor Discharges".

Awards being made by the various Districts for 1939 papers will be announced in future issues, as the information becomes available.

Branch • • • •

Annual Student Conference Held by District 4 Branches

The annual conference of AIEE Student Branches in the Southern District (4) was held at Mississippi State College, State College, Miss., April 11–13, 1940. About 175 delegates attended the conference, at which Dean L. L. Patterson, District chairman of student activities, presided. The program included a general session and a technical session on April 12, a business meeting April 13, a smoker April 11, given by the local chapter of Tau Beta Pi, and the annual banquet April 12. President F. Malcolm Farmer was the principal speaker at the opening session.

The six papers selected by the papers committee for final competition for the three cash prizes given by the Mississippi State College Branch, and presented at the technical session, were:

TECHNOLOGICAL UNEMPLOYMENT—AN ENGINEERING PROBLEM, **E. A. Kehoe,** University of Alabama

THE SANTEE-COOPER PROJECT, **R. G. Fellers,** University of South Carolina

THIRTY-PHASE MERCURY-ARC RECTIFICATION, **J. S. McQueen,** University of Tennessee

THE T RAY (THE TUBE RAY), **L. L. Anderson,** Speed Scientific School, University of Louisville

COMPARISON OF THE OPERATION OF 220-VOLT METERS ON 220- AND 208-VOLT CIRCUITS, **J. W. Wilkinson** and **W. M. Healy, Jr.,** North Carolina State College

CONSTRUCTION OF A FREQUENCY STANDARD, **M. M. Zemek,** Georgia School of Technology

First prize ($15) was awarded to L. L. Anderson; second prize ($10) to J. W. Wilkinson and W. M. Healy, Jr.; third prize ($5) to E. A. Kehoe. Awards were made at the annual banquet, at which District Vice-President Fred R. Maxwell, Jr., presided and G. W. Thaxton (M'36) chief engineer, Rural Electrification Administration, was principal speaker.

At the business meeting, April 13, distribution of District-conference prize-winning papers to the other Branches in the District was discussed. The conference voted to ask the AIEE board of directors to allow the Branch of which the student winning first prize is a member to use not more than $5 of its annual allotment for printing and mailing copies of the winning paper. Selection of papers for presentation at District conferences was discussed and it was voted to leave to the discretion of the papers committee the number to be presented.

The conference voted to meet next year at Tuscaloosa, Ala., at the invitation of the University of Alabama. Proposals for a meeting at Tulane University, New Orleans, in connection with the next District meeting to be held in that city, or at the University of Kentucky, Lexington, if a District meeting is not held in New Orleans in 1941, were favorably considered.

Professor W. J. Miller, University of Alabama, was elected District chairman of student activities for the term beginning August 1, 1940, and designated as counselor delegate of the Southern District to the forthcoming summer convention.

Conference on Student Activities Held by District 6

The 13th annual conference on student activities of the North Central District (6) was held April 19–20, 1940, at the University of North Dakota, Grand Forks. The program included two technical sessions, a general session, a business meeting of Student Branch counselors, and a banquet.

At the technical sessions on April 19, the following student papers were presented:

Morning session

TEST OF INSULATION BY POWER-FACTOR AND WATTS-LOSS METHOD. **Donald Riggs**, South Dakota State School of Mines

THE ACCENTUATION OF HARMONICS BY STATIC CONDENSERS USED FOR POWER-FACTOR CORRECTION. **H. A. Woll**, North Dakota State College

FREQUENCY MODULATION. **Clifford Thomforde**, University of North Dakota

FREQUENCY MODULATION. **Franklin Ordung**, South Dakota State College

APPLICATION OF THYRATRON TUBES. **Kenneth Beach**, University of Wyoming

Afternoon session

FREQUENCY CONTROL. **Stanley Case**, Colorado State College

HIGH-STABILITY GAIN IN REGENERATIVE AMPLIFIERS. **Harold Crispell** and **Clyde Hartman**, University of Colorado

ALL-IRON TRANSFORMERS AND REACTORS. **Robert Boyles** and **William Hinch**, University of Denver

DESIGN OF A LOW-COST AMATEUR RADIO TRANSMITTER. **H. W. Berry**, University of Nebraska

Prize awards, announced at the banquet April 19, were as follows: District prize for Branch paper Stanley Case; first honorable mention, Harold Crispell and Clyde Hartman; second honorable mention, Franklin Ordung. Feature speaker at the banquet was District Vice-President A. L. Turner.

The business meeting of Student Branch counselors was attended by the following:

Counselors: G. H. Sechrist, University of Wyoming; F. B. Beatty, Colorado State College; H. B. Palmer, University of Colorado; B. E. Cohn, University of Denver; L. A. Bingham, University of Nebraska; H. S. Rush, North Dakota State College; W. H. Gamble, South Dakota State College; J. O. Kammerman, South Dakota State School of Mines; H. F. Rice, University of North Dakota.

Others: Dean H. M. Crothers, South Dakota State College; A. L. Turner, District vice-president; I. M. Ellestad, District secretary.

The meeting voted to hold the 1941 conference on student activities at the University of Denver, Denver, Colo., April 18–19. Professor H. F. Rice, University of North Dakota, was elected chairman of the District committee on student activities for 1940–41 and counselor delegate to the 1940 summer convention. Changes in regulations governing student prize papers were discussed, and the recommendation made that Districts set their own qualifications for awards, but follow national rules in judging papers.

Standards • • •

Report on Wave Form in Dielectric Power-Factor Measurements

As a result of a request of the ASA committee on insulated wires and cables, the AIEE committee on instruments and measurements appointed a subcommittee* to study the effect of wave form in power-factor measurements and to suggest which of the following terms should be used: form factor, deviation factor, or distortion factor. The report which follows applies to power-factor tests made on commercial electrical insulating materials and insulation of electrical equipment where such tests are required by specifications. The recommendations apply to tests made at audio and radio frequencies as well as to tests made at power frequencies. Where very accurate measurements are required, as in certain research investigations, greater restrictions on wave form and measuring equipment are necessary as indicated.

FORM FACTOR

As given by AIEE definition, 05.05.260,

"The form factor of a symmetrical alternating quantity is the ratio of the effective value of the quantity to its half-period average value."

The form factor for a pure sine wave is 1.11. The form factor for a peaked wave is higher than 1.11; for a flat-topped or a saddled wave it is less than 1.11. Although form factor gives an idea of the wave shape, it does not disclose the extent of harmonic content. A form factor different from 1.11 indicates presence of harmonics, yet a form factor of 1.11 does not prove the absence of harmonics, inasmuch as distorted wave forms are possible which have a ratio of effective to average value of 1.11.

In view of this objection, form factor is not recommended for specifying wave form in dielectric-power-factor measurements.

DEVIATION FACTOR

As given by AIEE definition, 10.95.420,

"The deviation factor of a wave is the ratio of the maximum difference between corresponding ordinates of the wave and of the equivalent sine wave to the maximum ordinate of the equivalent sine wave when the waves are superposed in such a way as to make this maximum difference as small as possible."

The deviation factor indicates presence of distortion, and fixing an upper limit to the deviation factor limits the peak voltage of the wave. It does not indicate the relative amount of fundamental and harmonic components to that of the total wave.

The deviation factor requires a trace of the wave form.

In view of these objections, deviation factor is not recommended for specifying wave form in dielectric power-factor measurements.

DISTORTION FACTOR

As given by AIEE definition, 10.95.430,

"The distortion factor of a voltage wave is the ratio of the effective value of the residue after the elimination of the fundamental to the effective value of the original wave."

The distortion factor gives a measure of the harmonic content present in proportion to the total wave. Fixing an upper limit to distortion factor limits the maximum rms value for the harmonic content with reference to the total wave. The distortion factor may be measured with commercially available equipment, and a trace of the wave form is not required.

In view of the advantages in the use of distortion factor as compared to form factor or deviation factor, it is recommended that distortion factor be adopted for specifying wave form in dielectric-power-factor measurements.

CREST FACTOR

The crest factor of a wave is defined as the ratio of the maximum value to the effective value of the wave. The crest factor for a pure sine wave is 1.414; for a peaked wave, greater than 1.414; for a flat-topped or a saddled wave, less than 1.414.

CREST-DEVIATION FACTOR

The crest-deviation factor of a wave is the departure of the crest factor from 1.414, calculated in percentage. For a pure sine wave it is zero; for a peaked wave, greater than zero; for a flat-topped or a saddled wave, less than zero. The crest-deviation factor is never greater than the deviation factor, yet fixing an upper limit to the crest-deviation factor limits the peak voltage of the wave. It may be determined with commercially available equipment, and a trace of the wave form is not required.

For the particular case of a single harmonic distorting a wave in a peaked direction, both the distortion factor and the maximum crest-deviation factor closely follow the percentage of the harmonic in the wave, as may be seen from the tabulation below:

Distortion Factor and Maximum Crest-Deviation Factor for Varying Amounts of a Single Harmonic

Harmonic as Percentage of Fundamental	Distortion Factor (Per Cent)	Crest Factor, Peaked Wave	Crest-Deviation Factor (Per Cent)
0	0	1.414	0
5	4.994	1.483	4.9
10	9.950	1.548	9.5

When more than one harmonic is present in the wave, it is theoretically possible for the crest-deviation factor considerably to exceed the distortion factor. In the case of actual alternator wave shapes, however, extensive analyses have indicated that the ratio of the crest-deviation factor to the distortion factor is usually less than 1.4.

The advisability of placing a limitation on the crest-deviation factor of voltage waves used in measuring dielectric power factor is discussed later in the report.

EFFECT OF APPARATUS UNDER TEST ON WAVE FORM

When the charging current of the apparatus under test is such that it might appreciably increase the distortion of the voltage wave, the wave form should be determined with the apparatus under test or an equivalent capacitance connected to the voltage source.

EFFECT OF HARMONICS ON DIELECTRIC POWER-FACTOR MEASUREMENTS

When harmonics are present in the voltage of the power source, the measured power factor of a dielectric depends on:

1. Variation of dielectric properties with frequency
2. Variation of dielectric properties with voltage
3. Method of measurement
   - *A*. By measurement of power loss
     - (*a*). Calorimeter
     - (*b*). Electrometer
     - (*c*). Dynamometer

* Membership of the subcommittee: G. M. L. Sommerman, *chairman*, E. D. Doyle, Paul MacGahan, D. F. Miner, E. J. Rutan, E. H. Salter, C. T. Weller. (A. C. Seletzky, deceased, was chairman until May 1938.)

B. By measurement with a power-factor bridge

(*a*). Dependence of bridge balance on frequency and the frequency response of the null detector

In general, the power factor of a dielectric varies with frequency, but as long as the dielectric currents vary nearly linearly with voltage, and there is no appreciable heating caused by the harmonics, the power factor of the dielectric engendered by the fundamental frequency will be independent of harmonic content. Thus, measurement of power factor by any method which is not responsive to the harmonic frequencies will permit a determination independent of harmonic content and a function of fundamental frequency only.

If the voltage applied to the dielectric is of magnitude sufficient to produce ionizing gradients, a peaked wave might produce greater ionization than an equivalent sine wave. This suggests that a limitation be placed on the crest-deviation factor of the voltage wave. It is not necessary that the limitation be very drastic, however, because ionization in dielectrics usually increases only gradually with increasing voltage. It is therefore recommended that the crest-deviation factor be limited to less than ten per cent.

When the power factor of a dielectric is determined by measuring the dielectric loss with a calorimeter, electrometer, or dynamometer, the value obtained generally will be dependent on the distortion factor of the voltage wave. This is also true to some extent in power-factor-bridge measurements when a null detector with a broad frequency response is used. If the harmonics are known, and sufficient experimental data are available on the variation of dielectric properties with frequency for the dielectric under test, the power factor for a sine wave of fundamental frequency may be computed by calculations of the dielectric loss involved for each harmonic voltage. A comprehensive investigation of this phase of the question, sufficiently exhaustive to be of value, would require the investigation of different types of dielectrics with various kinds of wave forms, containing varying percentages of various harmonics at various amplitudes and phase angles. It is suggested that such an investigation would make an interesting research problem. This subcommittee, however, does not consider it necessary to undertake the investigation because in many cases it has been found that a small amount of distortion produces only a small error in power factor, and because this source of error can be effectively eliminated by the use of measuring apparatus which is not responsive to harmonic frequencies.

In bridge measurements, the effect of harmonics may be eliminated by making the null detector irresponsive to the harmonic frequencies. For example, a null detector tuned to the fundamental frequency or a tuned circuit ahead of the null detector may be used. A precaution which should be observed in this connection, if an amplifier is used ahead of the apparatus in which the frequency response is limited, is the necessity for linear amplification; otherwise harmonics can combine to produce a voltage of fundamental frequency at the amplifier output (W. M. Goodhue, *Journal* of the Franklin Institute, volume 217, 1934, page 87).

As far as could be ascertained from any indications in the literature, or from the experience and knowledge of any of the members of the subcommittee, considerable distortion does not influence to any appreciable extent the power-factor readings obtained with power-factor bridges equipped with properly tuned null-detector circuits. Available test data in this connection indicate that a distortion factor of ten per cent will not appreciably impair the accuracy of power-factor readings. On this basis it is safe to place a limiting value of five per cent to distortion factor.

RECOMMENDATIONS

As a result of these considerations, this subcommittee recommends that: Distortion factor should be used for the specification of voltage wave form of the power source employed in measurements of the power factor of dielectrics.

The distortion factor should be limited to five per cent.

The crest factor should not exceed that of a sine wave by more than ten per cent.

When accurate dielectric power-factor measurements are required, a sine-wave voltage source should be used, or measuring equipment which is insensitive to harmonic frequencies should be used.

Personal . . .

E. C. Crittenden (A'19, M'22) assistant director of the National Bureau of Standards, Washington, D. C., has been elected president of the United States National Committee of the International Electrotechnical Commission. Born December 19, 1880, at Oswayo, Pa., he received the degree of bachelor of arts at Cornell University, Ithaca, N. Y., where he later did graduate work in physics and mathematics while holding the position of instructor in physics, 1905–09. He was appointed assistant physicist at the Bureau of Standards in 1909 and later associate physicist and physicist. In 1921 he was made chief of the electrical section and since 1933 has been assistant director of the Bureau. He has represented the Bureau on the standards council of the American Standards Association since 1924, and has been a member of the electrical standards committee of the ASA and the USNC since 1931. He is a past president of the United States National Committee of the International Commission on Illumination, of the Illuminating Engineering Society, and of the Optical Society of America, and has also been active in the American Physical Society, American Institute of Physics, and American Association for the Advancement of Science. He was chairman of the AIEE committee on research 1938–39.

L. V. Bewley (A'27, M'37) has been appointed professor and head of the department of electrical engineering, Lehigh University, Bethlehem, Pa., effective September 1, 1940. He was born December 19, 1898, at Republic, Wash., and received the degree of bachelor of science in electrical engineering from the University of Washington in 1923, and that of master of science from Union College in 1927. He became associated with the General Electric Company in 1923 and has continued with the company ever since, his present position being research engineer at Pittsfield, Mass. He completed the General Electric test course, advanced course, and co-operative course with Union College, the last in preparation for the master's degree, and has taught for a number of years in the company's courses for engineering graduates. He is the author of a book and many technical papers. In 1932 he received the AIEE national best paper prize and he has received the Charles A. Coffin Award for "outstanding contributions to the knowledge of lightning and traveling-wave phenomena". He is a member of Sigma Xi and Tau Beta Pi.

H. B. Bryans (M'17, F'18) executive vice-president, Philadelphia Electric Company, Philadelphia, Pa., has been made a director of the company. He has been a vice-president since 1929 and executive vice-president since 1938. **Raymond Bailey** (A'17, M'26) formerly assistant electrical engineer in the electrical-engineering division of the company, has been appointed assistant purchasing agent. Mr. Bailey, who is chairman of the AIEE committee on power transmission and distribution, has been with the company since his graduation in 1916. He is succeeded as assistant electrical engineer by **L. R. Gaty** (A'39) formerly assistant to the general superintendent of transmission and distribution, suburban divisions. **C. E. Nelson** (M'35) formerly superintendent, service maintenance division, has been appointed division superintendent of the eastern division of the company.

Eugene Vinet (A'13, M'25) has been appointed executive secretary of the National Electrical Manufacturers Association. A native (1888) of Montreal, Can., he graduated in electrical engineering at McGill University in 1911. He has been associated with the Shawinigan Water and Power Company, Montreal; the Middle West Utilities Company, Chicago, Ill., and since 1931 with the Edison General Electric Appliance Company, Inc., Chicago.

E. E. Kleinschmidt (M'22) president, Kleinschmidt Laboratories, Inc., Highland Park, Ill., and **H. L. Krum** (A'12, F'27) Beverly Hills, Calif., vice-president, Teletype Corporation, Chicago, Ill., have been awarded jointly the Edward Longstreth Medal of the Franklin Institute "in consideration of their part in the development of a successful electrically operated duplicate typewriting machine now known as the teletypewriter."

Roland Whitehurst (A'20, M'21) formerly manager, Washington, D. C., branch, Electric Storage Battery Company, has been appointed assistant general sales manager of the company, with headquarters at Philadelphia. He has been with the company since 1908 and manager of the Washington branch since 1920. **J. A. Klingensmith** (A'38) formerly a member of the sales

staff in Washington, has been made manager of the branch.

Mark Eldredge (A'14, F'33) has resigned as director of the electrical division of the City of Memphis, Tenn., Light, Water, and Gas Division. He took the position in 1939 when the city took over the Memphis Power and Light Company, of which he had been chief engineer since 1924. Mr. Eldredge, who is a director of the Institute, has not announced his future plans.

K. L. Howe (A'28, F'36) has been made manager in charge of sales for the Seattle, Spokane, and Tacoma offices of the Westinghouse Electric and Manufacturing Company. He has been associated with the company since 1924, with headquarters in Seattle except for the period 1925–27 which he spent in East Pittsburgh and the past year, during which he was at San Francisco.

A. M. Musgrove (A'30, M'37) formerly assistant distribution manager, Bergen division, Public Service Electric and Gas Company of New Jersey, has been transferred to the Newark headquarters of the company, as assistant engineer in the department of distribution engineering.

M. P. Doran (A'38) formerly junior engineer, Harry Alexander, Inc., Washington, D. C., is now employed as electrical superintendent for Arundle-Consolidated Engineering Companies at the United States Naval Air Station, San Juan, Puerto Rico.

J. C. Gaylord (A'11, M'26) formerly hydro engineer, Southern California Edison Company, Ltd., Los Angeles, Calif., has been appointed superintendent of hydro generation.

R. E. Roesch (A'25, M'38) formerly division engineer, Virginia Public Service Company, Alexandria, is now associated with Stone and Webster Engineering Corporation, Boston, Mass.

L. G. Snyder (A'23, M'35) formerly sales manager, Landis and Gyr, New York, N. Y., is now sales manager in charge of central-station sales, Metropolitan Device Corporation, Brooklyn, N. Y.

W. C. Kalb (A'13, F'40) formerly in the advertising department of the Carbon sales division, National Carbon Company, Inc., Cleveland, Ohio, has been made commercial engineer of the division.

F. B. Doolittle (A'26, M'33) formerly distribution engineer, Southern California Edison Company, Ltd., Los Angeles, Calif., has been assigned to general engineering work with the title of electrical engineer.

V. B. Wilfley (A'26, M'37) engineering supervisor, Westinghouse Electric and Manufacturing Company, has been transferred from Portland, Ore., to Seattle, Wash., by the company.

G. K. Bennison (A'39) has been employed as an assistant in the ceramics laboratory, AC Spark Plug Division, General Motors Corporation, Flint, Mich.

H. P. Liversidge (A'12, M'17) president, Philadelphia (Pa.) Electric Company, has been elected a director of the United Gas Improvement Company, Philadelphia.

Obituary • • •

Edwin Fitch Northrup (A'01, M'09, F'13) vice-president and technical adviser, Ajax Electrothermic Corporation, Trenton, N. J., died at Princeton, N. J., April 29, 1940. He was born February 23, 1866, at Syracuse, N. Y., received the degree of bachelor of arts from Amherst College in 1891, and was a graduate student in physics at Cornell University and at Johns Hopkins University. At the latter he held fellowships for two years and received the degree of doctor of philosophy in 1895. He spent the following year in practical electrical work in Utah and Montana, and in 1896 was appointed associate professor and head of the department of physics at the University of Texas, Austin. During 1897–98 he was employed in the testing department of the Westinghouse Electric and Manufacturing Company, leaving to assist in the development of the Rowland multiplex printing telegraph system. He was chief engineer of the Rowland Telegraph Company 1898–1902. He was one of the founders of the Leeds and Northrup Company, manufacturers of electrical instruments, Philadelphia, Pa., and its secretary 1903–10. In 1910 he became assistant professor of physics at Princeton University, Princeton, N. J., and continued his teaching and research there until 1919. During this period he began the development of the coreless induction furnace, which is regarded as perhaps his leading contribution. From 1916 to 1920 he was president and technical adviser of the Pyroelectric Instrument Company, which he founded, and in 1920 he assumed the position with the Ajax Electrothermic Corporation which he held at the time of his death. He held over 100 United States patents, was the author of various textbooks and many technical papers, and was also a member of the American Association for the Advancement of Science, Electrochemical Society, Franklin Institute, and Inventors' Guild. He received the Bronze Medal of the Paris Exposition, 1900; the Edward Longstreth Medal, 1912; the Elliott Cresson Medal, 1916; and the Edward Goodrich Acheson Gold Medal, 1931. He was honored in 1932 as one of the 12 leading American inventors of the day and recently was cited as a "modern pioneer".

David Barker Rushmore (A'95, M'02, F'13) retired consulting engineer, General Electric Company, died May 5, 1940, at New York, N. Y. He was born at Old Westbury, N. Y., August 21, 1873, and received the degrees of bachelor of science in engineering, Swarthmore College, 1894; mechanical engineer (electrical engineering) Cornell University, 1895; civil engineer, Swarthmore, 1897; and the honorary degree of doctor of science from Swarthmore in 1923. In 1895–96 he was an inspector for the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., and in 1896–97 foreman of the testing department, Royal Electric Company, Montreal, Que., Can. After recovery from an accident he became a design engineer for the Stanley Electric Manufacturing Company, Pittsfield, Mass., continuing in that position until 1905 when he went with the General Electric Company, Schenectady, N. Y., as an engineer in the power and mining department. He became chief engineer of the department in 1907, and held that position until 1922. He was consulting engineer for the company 1922–25, until his retirement. He was president of the Espanol-Americano Company, and vice-president and director of the Spanish-American Fruit Company. He was a delegate to several meetings of the World Power Conference, and was also a member of The American Society of Mechanical Engineers, American Society of Civil Engineers, American Institute of Mining and Metallurgical Engineers, Electrochemical Society, American Association for the Advancement of Science, Société Française des Électriciens, and other organizations. He was the author of one book and many technical papers.

Walter S. Rugg (A'02, M'13) retired vice-president, Westinghouse Electric and Manufacturing Company, died in New York, N. Y., April 25, 1940. He was born in Broadhead, Wis., in 1866, and received the degree of bachelor of science from Laurence College in 1886 and that of master of science from Cornell University in 1892. Later that year he went with the Westinghouse company as a student engineer at Pittsburgh, Pa., continuing with the company until his retirement. He was transferred to Chicago, Ill., as district engineer in 1895, and in 1901 came to New York as special sales engineer. He was made manager of the New York office in 1909, continuing in that position until 1917, when he was made manager of the railway department at East Pittsburgh. Shortly afterward he was made manager of the marine department also, and in 1922 became general sales manager of the company. He was made a vice-president in 1925, in charge of engineering and sales activities. He retired in 1935. He was a manager of the AIEE 1910–13, and was also a member of the American Association for the Advancement of Science, Franklin Institute, and other organizations.

Ira Walton Henry (A'01, M'13) consulting engineer, New York, N. Y., died in Old Greenwich, Conn., April 25, 1940. He was born at Albany, N. Y., in 1869 and educated in Boston, Mass. From 1889 to 1892 he was an electrician at the New York central station of the Thomson-Houston Electric Company, and for the next four years was an electrical engineer for the Bishop Gutta Percha Company, manufacturing electric wires and cables. In 1896 he became a cable engineer for the Safety Insulated Wire and Cable Company, designing, manufacturing, and laying submarine cables. He later went into private practice as a consulting engineer. He devised a system of electrically lighted buoys used in New York Harbor for some years, and developed various other inventions. During the last ten years he had been chiefly concerned with the development of patents on electrical processes in oil refining. For this purpose he had formed the Ionizing Corporation of America, of which he was president at the time of his death.

John Theodore Graff (A'21, M'27) assistant vice-president, Chesapeake and Potomac Telephone Companies, Washington,

D. C., died March 18, 1940. He was born December 1, 1877, at Washington, and received the degree of mechanical engineer from Cornell University in 1900. He was employed immediately after graduation by the Western Electric Company, New York, N. Y., and in 1901 was transferred to the New York and Pennsylvania Telephone and Telegraph Company, as wire chief at Binghamton, N. Y. The following year he became wire chief at Baltimore, Md., for the Chesapeake and Potomac Telephone Company of Baltimore City, becoming district plant supervisor in 1909 and division plant engineer in 1913. During 1917–19 he served as captain in the Signal Corps of the United States Army, and was commissioned as major in the reserve corps on leaving the service. He returned to the office of the general plant manager of the Chesapeake and Potomac Telephone Companies in Baltimore. He was appointed general plant supervisor in 1927, chief engineer for Virginia in 1929, and assistant vice-president in 1939. He was chairman of the AIEE Virginia Section, 1933–34.

George Clayton Dill (A'13, M'22) electrical engineer, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., died April 1, 1940. He was born September 24, 1884, at Swanton, Ohio, and received the degree of bachelor of science in electrical engineering from Purdue University in 1909. After six months as an apprentice with the Fairbanks Morse Electrical Company, Indianapolis, Ind., he became an apprentice in the switchboard-engineering department of the Westinghouse company. In 1911 he became an electrical engineer in the supply-engineering department, handling design and application of lightning arresters, with particular attention to electrolytic arresters. He continued in that work until 1932, when he was transferred to the switchgear-engineering department of the Westinghouse company. He was the author of various papers for technical publications.

Julio Lagomasino, Jr. (A'38) engineer, Compania Cuba de Electricidad, Havana, Cuba, died recently, according to information just received at Institute headquarters. He was born November 15, 1912, at Havana, and received the degree of bachelor of science in electrical engineering at the Georgia School of Technology in 1937. Since 1937 he had been employed by the Compania Cuba de Electricidad, as student engineer and engineer.

Membership • •

Recommended for Transfer

The board of examiners, at its meeting on May 16, recommended the following members for transfer to the grade of membership indicated. Any objection to these transfers should be filed at once with the national secretary.

To Grade of Fellow

Copeland, C. A., assistant electrical engineer, Bureau of Power and Light, Los Angeles, Calif.
Dible, H. J., transmission and protection engineer, The Ohio Bell Telephone Company, Cleveland.
LeClair, T. G., supervising development engineer, Commonwealth Edison Company, Chicago, Ill.
Rollins, N. A., plant installation engineer, Commonwealth Edison Company, Chicago, Ill.
Smith, W. C., Engineer, General Electric Company, San Francisco, Calif.

5 to Grade of Fellow

To Grade of Member

Baker, R. M., research engineer, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.
Bower, G. W., district superintendent, Public Service Electric and Gas Company, Camden, N. J.
Boyce, H. A., district plant engineer, American Telephone and Telegraph Company, Cleveland, Ohio.
Diehl, F. V., relay engineer, Oklahoma Gas and Electric Company, Oklahoma City.
Evans, D. G., vice-president, Wisconsin Gas and Electric Company, Racine.
Gienger, J. A., assistant electrical engineer, Eastman Kodak Company, Rochester, N. Y.
Grimm, G. A., chief load dispatcher, Indiana Service Corporation, Fort Wayne.
Hazen, H. L., professor of electrical engineering, Massachussetts Institute of Technology, Cambridge.
Henderson, C. W., professor of electrical engineering, Syracuse University, Syracuse, N. Y.
Hyatt, A. P., general plant supervisor, Illinois Bell Telephone Company, Chicago, Ill.
Knotts, C. L., engineer, Westinghouse Electric and Manufacturing Company, Sharon, Pa.
Millard, T. O., application engineer, General Electric Company, Chicago, Ill.
Miller, S. O., chief electrical engineer, Lower Colorado River Authority, Austin, Tex.
Olson, P. R., electrical engineer, American Steel and Wire Company, Worcester, Mass.
Parrott, W. G., assistant electrical engineer, Tennessee Valley Authority, Chattanooga, Tenn.
Read, C. A., executive assistant, General Electric Company, Pittsfield, Mass.
Smith, H. E., line design engineer, Commonwealth Edison Company, Chicago, Ill.
Vivell, A. E., assistant professor, Princeton University, Princeton, N. J.
Wishard, W. W., station installation engineer, Commonwealth Edison Company, Chicago, Ill.

19 to Grade of Member

Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. Names of applicants in the United States and Canada are arranged by geographical Districts. If the applicant has applied for direct admission to a grade higher than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the national secretary before June 30, 1940, or August 31, 1940, if the applicant resides outside of the United States or Canada.

United States and Canada

1. North Eastern

Bartelink, E. H. B., General Electric Company, Schenectady, N. Y.
Edwards, R. D., Jr., 92 Warwick Avenue, Bridgeport, Conn.
Falk, M. C., Central New York Power Company, Syracuse, N. Y.
Larrick, C. V., General Electric Company, Schenectady, N. Y.
Winsor, L. P., Harvard University, Cambridge, Mass.

2. Middle Eastern

Agner, O. B., Westinghouse Electric and Manufacturing Company, Philadelphia, Pa.
Bray, F. E., Jr., Sun Shipbuilding & Dry Dock Company, Chester, Pa.
Cleaves, R. D., Allis-Chalmers Manufacturing Company, Pittsburgh, Pa.
Cornbrooks, C. W., United States Maritime Commission, Washington, D. C.
Cramer, F. W. (Member), Carnegie Illinois Steel Corporation, Pittsburgh, Pa.
Hipp, J. E., Consolidated Gas Electric Light and Power Company of Baltimore, Baltimore, Md.
Leonard, S. E., National Broadcasting Company, Inc., Cleveland, Ohio.
Lucas, J. S., Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.
MacLane, G. L., Jr., Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.
McKee, F. L., Philadelphia Electric Company, Philadelphia, Pa.
Radecky, P. P., Hickok Electrical Instrument Company, Cleveland, Ohio.
Snyder, R. R., Hartman Electrical and Manufacturing Company, Mansfield, Ohio.
Van Liew, A. B., Utilities Service Company, Allentown, Pa.
Van Sickle, M. E. (Member), Pennsylvania Power and Light Company, Williamsport.
Wickline, F. H., Duquesne Light Company, Springdale, Pa.
Wyman, B. W., General Electric Company, Philadelphia, Pa.

3. New York City

Di Stadio, D., Western Electric Company, New York, N. Y.
Giordano, A. B., Polytechnic Institute of Brooklyn, Brooklyn, N. Y.
Kittredge, L. E., (Member), American Telephone and Telegraph Company, New York, N. Y.
Mahoney, J. J., Jr., Bell Telephone Laboratories, New York, N. Y.
Sattan, J. K., 11 Caroline Avenue, Clifton, N. J.
Shepardson, E., Colvinex Corporation, New York, N. Y.
Smith, A. B., National Electrical Manufacturers Association, New York, N. Y.
Swanson, G. F., Bell Telephone Laboratories, New York, N. Y.

4. Southern

Boone, W. H., Fairbanks Morse and Company, New Orleans, La.
Giersch, O. L. (Member), Duke Power Company, Charlotte, N. C.
Guy, E. H., Florida Power and Light Company, Miami.
Kendrick, W. H. (Member), South Carolina Electric and Gas Company, Columbia.
McMeekin, F. R. (Member), South Carolina Electric and Gas Company, Columbia.
Reeves, J. H., Jr., Westinghouse Electric and Manufacturing Company, Greenville, S. C.
Rodgers, W. S. (Member), South Carolina Electric and Gas Company, Columbia.
Ryscuck, J., Seaboard Air Line Railway, Norfolk, Va.
Stevenson, J. R. (Member), Memphis Light, Gas and Water Division, Memphis, Tenn.
von Bose, Max, Florida Power and Light Company, Miami.
Weeks, J. L. (Member), South Carolina Electric and Gas Company, Columbia.

5. Great Lakes

Dinius, K. E. (Member), Carnegie Illinois Steel Corporation, Chicago, Ill.
Drake, G. F. (Member), Woodward Governor Company, Rockford, Ill.
Judd, R. C., Peoples Light Company, Davenport, Iowa.
McConnell, R. C., Joseph E. Seagram and Sons, Inc., Lawrenceburg, Ind.
McCurdy, B. H., Commonwealth and Southern Corporation, Jackson, Michigan.
Olsen, S. R., Commonwealth and Southern Corporation, Jackson, Mich.
Sever, L. J., Commonwealth and Southern Corporation, Jackson, Mich.

6. North Central

Wingfield, K. S. (Member), Public Works Administration, Kearney, Nebr.

7. South West

Donaldson, W. L., Texas Electric Service Company, Wichita Falls.
Hawkins, V. D., Arkansas Power and Light Company, Marion.
Learned, S. (Member), Phillips Petroleum Company, Bartlesville, Okla.
Weber, R. S. (Member), Rural Electrification Administration, Austin, Texas.

8. Pacific

Heintz, R. M. (Member), Jack Heintz, Ltd., Palo Alto, Calif.
Lidow, E., Emby Photographic Products, Inc., Los Angeles, Calif.
Miller, R. P. (Member), Miller Electric Construction Company, San Diego, Calif.
Van Meter, L. M., Pacific Gas and Electric Company, Oakland, Calif.

9. North West

Brunzell, G. M., Washington Water Power Company, Davenport.
Cromby, R. R., Department of Lighting, Seattle, Wash.
Hiatt, D. L., Northwestern Electric Company, Portland, Ore.
Johnson, E. E., Washington Water Power Company, Okanogan.
Polhemus, J. H. (Member), Portland General Electric Company, Portland, Ore.
Thompson, V. N., Washington Water Power Company, Lewiston, Idaho.

10. Canada

Bissett, D. P. M., 7214—105 A Street, Edmonton, Alberta, Canada.

Total, United States and Canada, 59

Elsewhere

Sharma, R. L., Raghunath Temple, Muzaffarabad, Kashmir, India.
Aras, B. K., Shikarpur Electric Supply Company, Ltd., Shikarpur, Sind, India.
Hirsch, W. (Member), Brazilian Telephone Company, Rio de Janeiro, Brazil, South America.
Benjamin, L., Power House, Veraval, Junagadh State, India.
Scheibe, W. K. (Member), Cia Minera de Oruro, Oruro, Bolivia, South America.
Mahanti, P. (Member), University College of Science and Technology, Calcutta, India.

Total, elsewhere, 6

Transactions

Preprint of Papers and Discussions Comprising Pages 1–64 of the 1940 Volume

The Characteristics and Power Requirements of Spinning Frames

E. A. UNTERSEE
NONMEMBER AIEE

THE POWER required to drive the many types of textile machines has always been an important problem confronting the manufacturer of all the textile fibers, especially the cotton-goods manufacturer, who leads all other branches of the industry.

When the majority of cotton mills were driven by steam or water power, this problem was not critical, but when the large groups of machines were broken down to individual drives and smaller groups driven by electric motors, it assumed greater importance.

The earlier designs of large motors replacing the steam engine or water wheel were extremely liberal, and the addition of a few extra machines on a large motor-driven group seldom worried the manufacturer or the motor. A greater knowledge of fundamentals and the more economical use of materials today permits the design of more efficient motors, very close to their name-plate ratings, which demands a more accurate knowledge of power requirements in applying the motors.

Advancements in the manufacture of fabrics and the breaking up of group drives into individual motor applications for greater flexibility in operation necessitates a much closer study of the power requirements of the individual machines.

The usual method of meeting these problems was to take electrical instruments to the mills and make power tests on the machines in question, recording all textile data at the same time. These data were compiled and served as a basis for determining power requirements in many other mills.

Paper number 39-103, recommended by the AIEE committee on industrial power applications, and presented at the AIEE North Eastern District meeting, Springfield, Mass., May 3–5, 1939. Manuscript submitted February 17, 1939; made available for preprinting March 30, 1939.

E. A. Untersee is with the General Electric Company, Schenectady, N. Y.

Complete segregation and analysis of the power requirements of various parts of the machines were seldom made.

Table I. Spinning-Frame Tests—Frame Data

Width—39 inches, length—51 feet
Number of spindles—360
Number operated during tests—348; others removed
Whorl diameter—1 1/8 inches
Gauge spindle—3 1/4 inches

Width tape—5/8 inch
Traverse—7 inches. With 2-inch and 2 1/4-inch ring traverse increased to 7 3/8 inches
Cylinder diameter—9 inches
Cylinder bearings—ball
Ring diameter—1 1/2 inches, 1 3/4 inches, 2 inches, 2 1/4 inches

Type ring—number 2 FDA
Traveler weight and number—number 2 flange—5/0–6 1/2 GR Bowen used on doffs 1–2–3. Doff number 5 used number 2 travelers. Doffs 6–7 use number 2 travelers. Two flange circle Al, style *RP*
Number yarn spun—33/1. Twist per inch—13
Doffs 5–6–7 20*s* yarn
Yarn spun—warp
Two-ply roving—3.50 hank

Type builder—combination set for warp
Thread board—traversing
Diameter front roll left side, 1 inch; diameter neck, 0.750 inch
Diameter front roll right side, 1 inch; diameter neck, 0.750 inch
Diameter middle roll left side, 7/8 inch; diameter neck, 0.592 inch

Diameter middle roll right side, 7/8 inch: diameter neck, 0.650 inch
Diameter back roll left side, 7/8 inch; diameter neck, 0.592 inch
Diameter back roll right side, 1 inch; diameter neck, 0.750 inch
Tape idler pulleys, ball bearing 2 3/4 inches diameter
Weight on front rolls four pounds

Gearing:

Cylinder	26 teeth
Jack	112 teeth
Twist	44 teeth
Front roll	100 teeth
Lay	51 teeth
Crown	140 teeth

Top-roll gearing:

Back roll left side	33 teeth
Back roll right side	34 teeth
Middle roll left side	29 teeth
Middle roll right side	26 teeth
Intermediate each	40 teeth
Back roll (large) each	106 teeth

Top rolls cork—front and back

Weighting of top rolls:

Front	= 22 pounds
Middle	= 15 pounds
Back	= 9 pounds

The power required to drive the machinery in the yarn spinning department usually represents approximately 50 per cent of the total power required for operating the mill, and power studies have usually been confined to this department because it has the greatest possibility of economic improvement.

In recent years many changes in spinning-machine designs have been made. Longer frames, larger spindles, bobbins capable of handling more yarn have been demanded by the textile manufacturer. These new designs and improved materials have made it possible to raise the operating speed, increase production, and reduce manufacturing and operating costs, necessitating more accurate power information.

The machinery manufacturers, the textile manufacturers, and the electric-motor manufacturers are vitally concerned with the problems of power requirements.

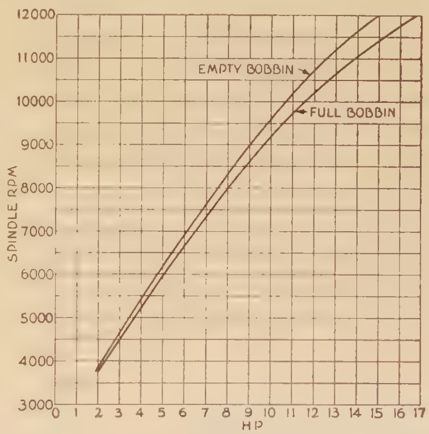


Figure 1. Spinning-frame tests—348 spindles, 1 1/2-inch-diameter ring

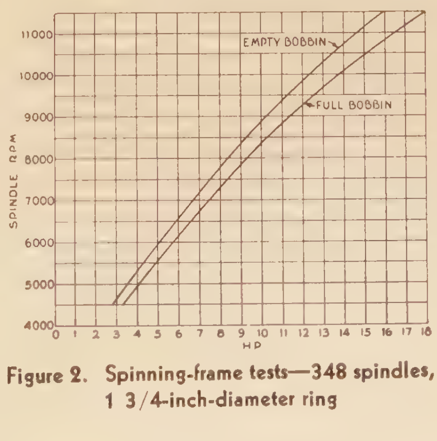


Figure 2. Spinning-frame tests—348 spindles, 1 3/4-inch-diameter ring

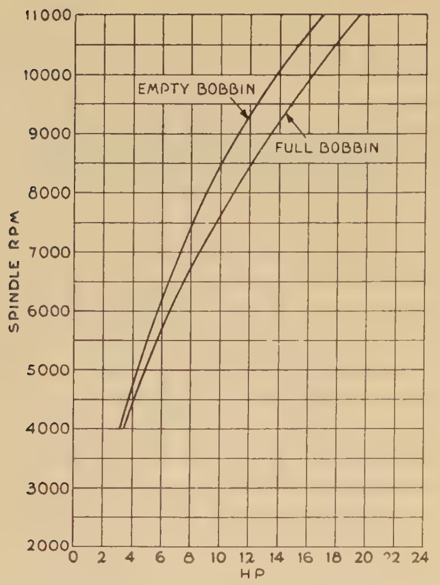


Figure 3. Spinning-frame tests—348 spindles, 2-inch-diameter ring

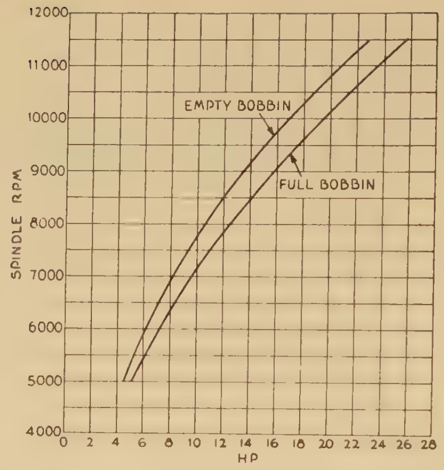


Figure 4. Spinning frame tests—348 spindles, 2 1/4-inch-diameter ring

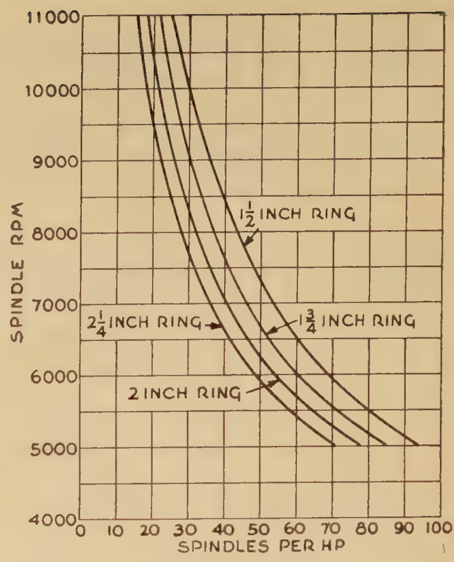


Figure 6. Spinning-frame tests—348 spindles

The machinery manufacturers are interested in producing the most efficient operating machines for the textile manufacturer. The textile manufacturer, in turn is interested in higher quality and higher production at minimum cost, while the motor manufacturer is interested in designing motors with characteristics which will suit the machine and meet all of the operating conditions.

The generally accepted methods of testing spinning frames have never disclosed power requirements of the different elements of the machine, which could be relied upon generally for all spinning machines. Tests made on a number of duplicate frames, all spinning the same size yarn, show wide variations in power; so much so, that it is necessary, for interchangeability of motors, to use ratings which will meet the maximum power conditions.

The lack of accurate information on the power requirements of the various elements of a spinning frame and the effect of changes in ring diameter, spindle speed, number of spindles, and different sizes of yarn on the power requirements has stressed the need for a careful analysis of the problem.

With this in mind, extensive power tests were made to establish the characteristic requirements and derive an empirical formula, if possible, which can be relied upon by the machinery manufacturers and the textile manufacturers to determine the horsepower required to drive the various types of spinning machines.

A modern 348-spindle frame with long-draft spinning system was selected for making the tests. The data in table I will show all the mechanical features of the frame.

Tests were carried on throughout the spinning cycle starting with a $1^1/_2$-inch-diameter ring and a medium-size spindle, followed by similar tests after changing the size of the ring to $1^3/_4$ inches diameter. The yarn spun during these tests was an average of 30*s* yarn, this being what may be classified as medium-count yarn in a textile mill.

On the completion of these power tests, a series of breakdown tests were carried on to determine the separate power requirements of the various elements of the frame, such as the cylinder only, cylinder and spindles; cylinder, spindles and front rolls; cylinder, spindle, full bobbins builder and no rolls.

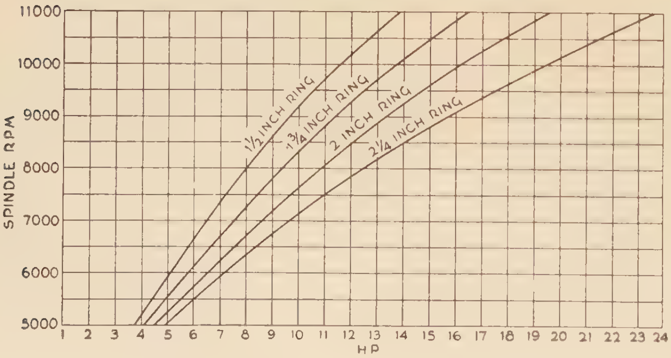


Figure 5. Spinning-frame tests — 348 spindles

Following these tests a heavier type spindle was installed on the frame with a two-inch-diameter ring and power readings taken throughout the spinning cycle.

After this test, the 2-inch-diameter rings were replaced by $2^1/_4$-inch-diameter rings and similar tests conducted followed by a set of breakdown tests. The yarn

Table II. Spinning-Frame Tests—Breakdown Tests

Small Spindles

Condition	Horse-power	Spindle RPM	
Cylinder, bare spindles, no steel rolls and no builder	2.0	4,115	
	2.9	5,488	
	4.0	6,860	
	6.2	9,227	
	8.6	11,234	
	12.5	13,618	
Cylinder, bare spindles, *front steel rolls* and no builder	2.6	4,061	
	5.2	7,063	
	6.3	8,090	
	9.0	10,348	
	11.0	11,869	
	13.5	13,139	
Cylinder, spindles, empty bobbins, no steel rolls, no builder	2.1	4,202	
	3.1	5,785	Empty bobbins, no appreciable power
	4.7	7,463	
	6.3	9,408	
	7.7	10,427	
	12.5	13,312	
Cylinder, spindles, empty bobbins, builder, no steel rolls	1.9	3,880	
	3.3	5,558	Builder, no appreciable power
	4.5	6,930	
	5.9	8,820	
	7.7	10,286	
	8.7	11,038	
	12.0	13,077	
Cylinder, bare spindles, builder, no steel rolls	2.1	4,163	
	3.5	5,864	
	4.9	7,212	
	5.8	8,294	
	7.5	9,862	
	13.0	13,800	
Cylinder, spindles, full bobbins and builder motion, no steel rolls	3.3	4,547	
	4.1	5,688	
	5.1	6,758	
	7.4	8,247	
	10.5	10,129	
	17.0	12,900	

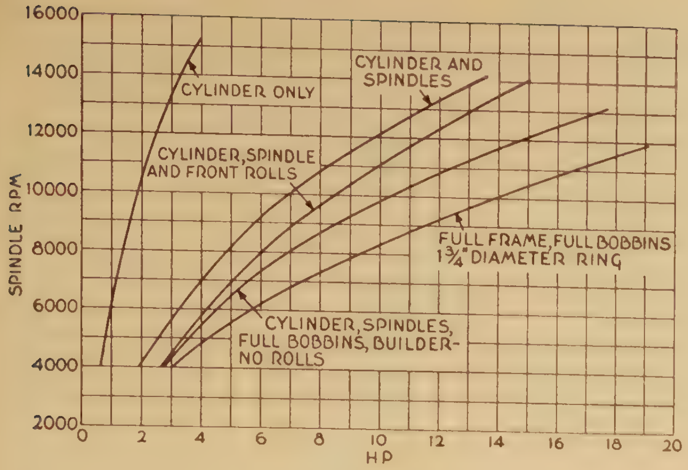


Figure 7. Spinning-frame tests—348 spindles, small spindles

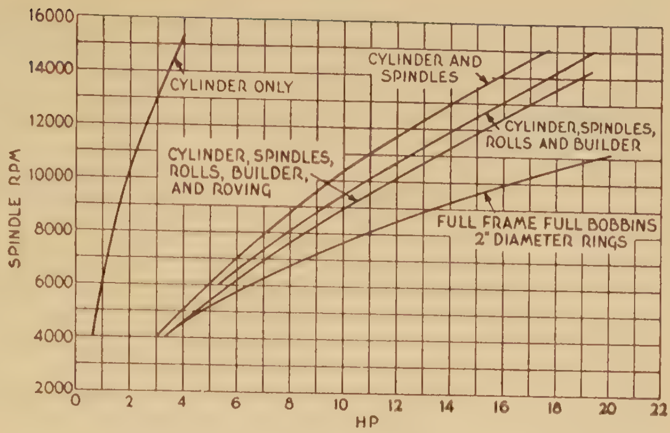


Figure 8. Spinning frame tests—348 spindles, large spindles

spun on the 2-inch and $2^1/_4$-inch rings was an average of 20*s* yarn.

During the spinning tests power readings were taken at the empty bobbin position at various spindle speeds and again at the full bobbin position with each size of ring.

The results of these power tests are shown on the accompanying curves for the four different ring diameters (figures 1, 2, 3, and 4).

As the most important data on these tests are the full-bobbin position, or maximum horsepower of the frame, the full-bobbin readings are plotted together

Table III. Spinning Frame Tests—Breakdown Tests

Large Spindles

Condition	Horse-power	Spindle RPM	
Cylinder only, no tapes	0.8	4,170	
	1.0	5,930	
	1.3	7,780	
	1.8	9,720	
	2.5	11,950	
	4.0	15,300	
Cylinder, bare spindles, no steel rolls, no builder	3.1	4,147	
	5.9	7,000	
	9.4	10,000	
	16.1	13,947	
	15.7	13,986	
Cylinder, bare spindles, no steel rolls, with builder	2.8	4,116	Builder, no appreciable power
	5.5	6,907	
	7.9	8,851	
	11.2	11,344	
	15.9	14,315	
Cylinder, bare spindles, front steel rolls, builder	3.3	4,061	
	5.5	6,287	
	9.3	9,023	
	13.9	11,908	
	16.6	13,429	
Cylinder, bare spindles, all steel rolls, builder	5.3	6,000	Back steel rolls, no appreciable power
	7.8	8,004	
	12.6	11,148	
	18.1	13,908	
Cylinder, bare spindles, all steel rolls, builder and roving	3.3	3,888	
	10.8	9,408	
	18.5	13,868	

and show very clearly the increase in power as the ring diameter increases, and also as the spindle speed is increased. It also shows that the ring diameter has a very important bearing on the power requirements of a spinning frame (figure 5). This is probably more clearly shown on the curve of spindles per horsepower when operating with different-diameter rings (figure 6).

The breakdown tests with either small or large spindles (figures 7 and 8) show definitely that the cylinder alone requires a very small percentage of the total power of the frame. The addition of spindles shows a very marked increase in the power required at various spindle speeds. The addition of the steel rolls does not materially increase the power. The addition of the full bobbins while not spinning shows a considerable increase in power which is due to windage and some small amount of friction. The full-power curve on these figures, which is the full-bobbin position while actually spinning yarn, shows a marked increase over the amount of power required by the cylinder, spindles, steel rolls, and full bobbins.

It is appreciated that the spindle speeds were increased beyond a point where practical spinning could be done, but this was necessary to establish the power requirements at high spindle speeds, and establish the characteristics of the frame.

The upper half of figure 9 is an analysis of the previous curves made and shows the characteristic increase in horsepower for various ring diameters plotted against the peripheral speed of the full bobbins in feet per minute. On this curve the solid lines are plotted from test data while the dotted lines are pro-

Table IV. Spinning-Frame Tests—Analysis

Ring Size (Inches)		Revolutions per Minute for Peripheral Speeds of Feet per Minute: 2,000	2,500	3,000	3,500	4,000	4,500	5,000	5,500	6,000
$1^1/_2$	Spindle speed	6,110	7,640	9,170	10,700	12,200	13,750	15,300	16,800	18,350
	Horsepower	5.25	7.5	10.0	13.2					
$1^3/_4$	Spindle speed	5,110	6,370	7,640	8,910	10,200	11,460	12,730	14,000	15,300
	Horsepower	4.25	6.45	8.75	11.22	14.25				
2	Spindle speed	4,370	5,460	6,560	7,650	8,750	9,840	10,290	12,000	13,100
	Horsepower	5.37	7.72	10.15	12.8	15.75	19.3			
$2^1/_4$	Spindle speed	3,490	4,500	5,400	6,300	7,200	8,100	9,000	9,890	10,800
	Horsepower			5.8	7.95	10.22	12.95	15.9	19.13	22.75

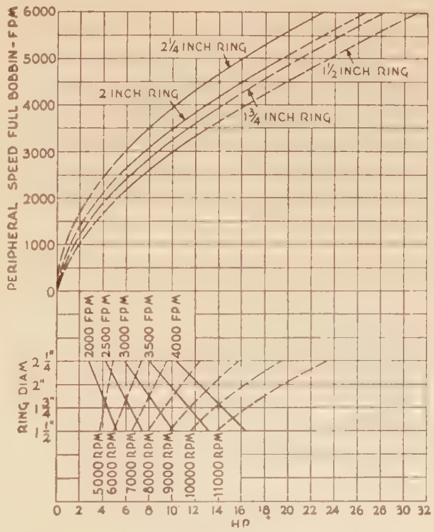


Figure 9. Spinning-frame tests—348 spindles, analysis

Carrier-Current Losses Measured and Interference Minimized on Boulder-Los Angeles Transmission Lines

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Synopsis: Two unusual facts were disclosed during the field testing of the supervisory-control carrier-current channel on the 287-kv Boulder Dam-Los Angeles transmission lines. Carrier-current losses were much higher than calculations and previous experience had indicated. The interference from power equipment arcs could not be isolated by the use of resonant choke coils, requiring special circuit designs for satisfactory operation.

Background

SUPERVISORY CONTROL for the operation of the circuit breakers, disconnecting and ground switches of the Boulder Dam-Los Angeles transmission lines uses a carrier-current channel. These are the highest voltage lines operating in the United States and there was, therefore, no definite information available on the losses to be encountered; nor was there much knowledge of the magnitude of interference that might be caused by static, corona, or arcs from power equipment. Field tests have been made which have brought to light some interesting facts. It is the purpose of this article to record these experiences so that future applications of a similar nature may be facilitated.

Interference

Line noise, lightning, and arcs from the operation of oil circuit breakers, disconnecting, and grounding switches create carrier-frequency waves on the lines which interfere with the reception of normal working carrier signals.

The interference due to line noise is ever present and changes over wide limits. Dry dust or sand-laden air blowing across the line produces some interference. Rain increases the interference level. Increase in corona and lightning during wet weather produces the maximum interference. To overcome line-noise interference on the 287-kv lines, it is necessary to have a carrier signal of ten milliwatts at the receiver, in order to provide a sufficient ratio of signal to interference for satisfactory operation. The receiver sensitivity can then be adjusted to give no receiver relay operations from interference. This minimum power value may be applied to lower-voltage lines also since the gradients are of the same order of magnitude.

Interference from disconnecting switches is very serious on long lines where the received signal is relatively low. Measurements indicated that the interference from a disconnecting switch opening the charging current of a 287-kv breaker bushing 180 miles away was approximately ten times that produced by maximum line noise. It was found that interference from the high-voltage lines was a maximum at a receiver when it was raining at the receiver location.

The resonant choke coils do not hinder the transmission of arc interference. The arcs of each phase go out every half cycle and re-establish. As the arc again breaks down, the steep wave front (practically square) produces a large band of frequencies which are not stopped by the resonant choke coils.

On opening a disconnecting switch, the arc continues for more than one second with gradually increasing interference. Its peak value occurs just before the arc is extinguished. The interference is greatest when the second disconnecting switch is opened on the end of an energized section since the capacity of the line raises the voltage at that point. The first disconnecting switch, in opening, only opens a parallel path with the last one and, therefore, results in opening a lower voltage arc. On closing a disconnect, the interference is of a lower level and shorter duration.

Oil circuit breakers when opening and closing any loads or line-charging current create the same magnitude of interference but last a very short time [two or three cycles (60)].

The interference from ground-switch operation is low in magnitude, being that of grounding the static charge stored on the de-energized line conductors. It is a maximum when grounding a section which is paralleling an energized line.

Effect of Interference on Signaling Codes

Practically all supervisory-control systems depend on a code of pulses for selection, indication, and operation. To dis-

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jections of these curves. It clearly shows a uniform power characteristic regardless of ring diameters

The lower part of figure 9 (solid lines) is interesting because it shows a decrease in power with increasing ring diameters at the same peripheral speed of the full bobbin, and also shows (dotted lines) an increase in power with increasing ring diameters at the same spindle speeds.

It would appear that approximately 65 per cent of the total load of a spinning frame is pure friction, and the balance windage and spinning.

From test data taken, it would appear that the friction load varies as the 1.42 power of the spindle speed. On the other hand test curves in figure 5 seem to indicate that the power of the full frame while spinning varies as the 1.68 power of the speed with a $1^1/_2$-inch ring, the 1.765 power with a $1^3/_4$-inch ring, the 1.865 power with a 2-inch ring, and the 1.99 power with a $2\,^1/_4$-inch ring.

To use this, one must have some definite power reading on the frame in question, but since this is not always available it would be much more satisfactory to have a formula which is based on spindle speed, ring diameter, and a constant from which the power of any frame may be calculated. For example the formula:

$$\text{Horsepower per spindle} = 0.000284 \times R^{1.42}\left(\frac{\text{rpm}}{1{,}000}\right)^{1.808}$$

seems to hold fairly well for the test data thus far obtained, but it may be necessary to modify this formula or introduce another constant to make it apply to larger ring diameters and twisting operations.

tinguish one code from another, the number and timing of the impulses must be of a definite character.

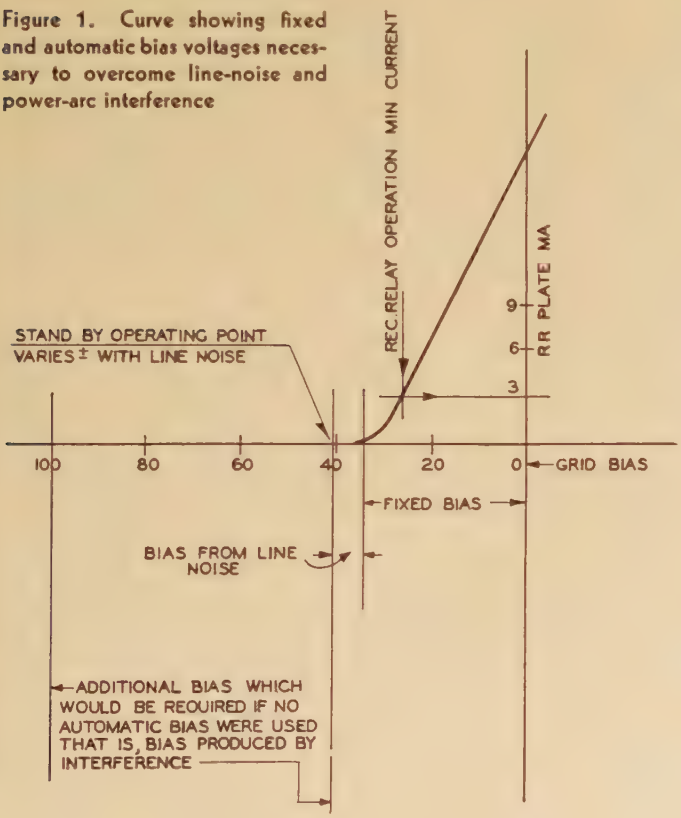
The effect of arc interference on the codes varies with the type of operation and the device being operated. First, consider operations by the dispatcher. During the selection and check, no operations of power equipment occur and there is no interference. The dispatcher then initiates the operation control code to start the remote apparatus to close or open, as the case may be. The interference starts here. On closing or tripping a circuit breaker, there is a short arc of one to three cycles depending on the speed of the breaker. To the carrier equipment this represents a short pulse. The breaker auxiliary switches, which initiate the supervision indication, operate about the same time. Should the interference pulse be permitted to operate the receiver relay, an extra pulse would be added to the indication code and thus cause the supervisory control equipment to lock-out. It is then necessary for the dispatcher to reset the equipment before the new indication is reported.

For disconnecting switches, the operation is different for opening and closing in the length of arcing time and the time when it occurs with respect to the supervisory code. In opening the switch, enough time elapses between the operation of the pallet switches which initiate the signal and the start of the arc to get the new signals properly registered. In closing, the arcing time is shorter and is complete before the pallet switches initiate the signal to indicate the position.

Automatic or manual operation of the equipment at the substation sends in a selecting code to the office, which is immediately followed by the indication code. With circuit breakers, the arcing is completed before the signalling begins, but may add onto the start of the selection code if the first pulse of the selection code occurs within 0.05 second of the arc pulse. In opening a disconnect from the dispatching office at Boulder, the signal is finished before the arc starts, while in closing the arcing is complete before the signalling begins.

It is advisable, therefore, to make the receivers inoperative when the arcs are occurring. This is done by rectifying the output of a separately tuned circuit (excited by components in the interference-signal of some frequency other than the frequency of carrier operation and preferably lower) and using it as a heavy negative bias on the receiver tubes. See figure 1. Thus, methods of overcoming the interference are (1) make the interference miss the time of signalling and (2) make the receiver less sensitive during the interference.

Figure 1. Curve showing fixed and automatic bias voltages necessary to overcome line-noise and power-arc interference



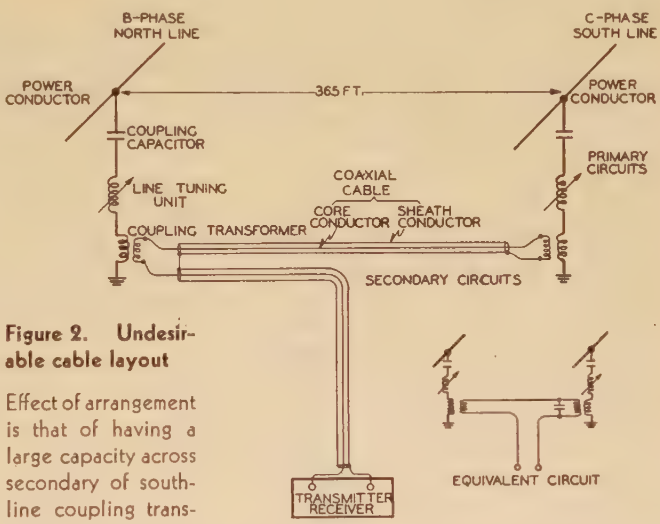


Figure 2. Undesirable cable layout

Effect of arrangement is that of having a large capacity across secondary of south-line coupling transformer. This is caused by the high capacity of sheath to ground of secondary cable, with abnormal line conditions, the resulting unbalance can create large carrier transmission losses

Carrier Transmission Losses

Probably the most interesting part of the field tests concerned the measurement and segregation of carrier transmission losses under various combinations of line sections in service.

In order to segregate the transmission losses into their component parts, it is advisable to divide them into their two main divisions. These are the primary or line circuits and the secondary or station losses.

Primary Circuits

High-voltage capacitors with a series tuning inductance and a coupling transformer are used to connect the carrier transmitters and receivers to the line. Paralleled tuned resonant choke coils are necessary in isolating the channel from spur lines and other paralleling circuits. These, with the line conductors are known as "primary" circuits and may be segregated into phase-ground, phase-phase, and phase-phase-ground connections.

Phase-to-ground transmission requires, for the same reliability, the most power per unit distance. It is useful for short distances (30 miles or so) at low-power (15 to 30 watts) inputs. The connection has the advantage of using the minimum of coupling capacitors, line tuning units, and resonant choke coils.

Phase-to-phase transmission will give about two to over three times the power per unit distance as compared to the phase-ground connection. (See appendix where the ratio was 3.25.) It has the lowest losses for channels on single-tower lines. On double-tower lines where a phase wire of each circuit is used, the phase-to-phase loss may not be much less

than phase to ground. The lower losses result in higher received carrier power. Also, the amount of coupling equipment is roughly twice that required for phase-to-ground connections.

Phase-to-phase-to-ground transmission is the most reliable. Under normal con-

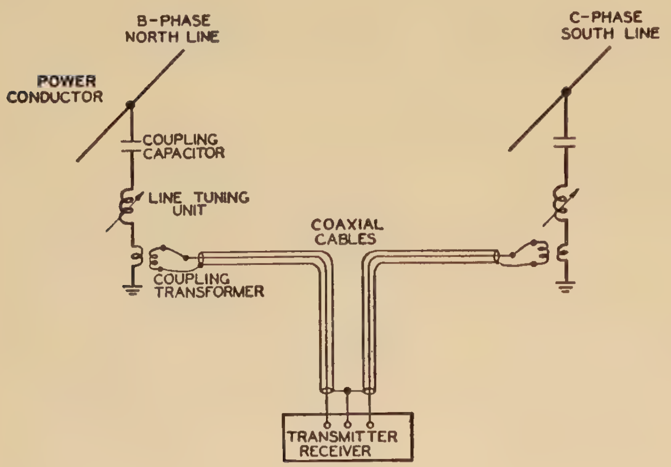


Figure 3. Desirable secondary cable layout

This layout gives a balanced cable arrangement which greatly reduces the carrier transmission losses under adverse line conditions. It is a three-wire system operating phase-phase-ground

ditions, this type of transmission has the advantage of phase-to-phase connections and operates phase to ground under adverse line conditions due to short-circuited or open-circuited line conductors. It requires the same power level needed for phase-to-ground transmission. Here also, the line-coupling and choke-coil equipment is twice that required for phase-ground transmission. This is the system in use on the supervisory-control system controlling the various switching devices on the Boulder Dam-Los Angeles twin-circuit transmission lines.

Secondary Circuits

The secondary circuits consist of the secondary windings of the coupling transformers, cable circuits, and the primary windings of the transmitter output as well as the receiver input transformer. The voltage ratio of the coupling transformer is chosen to match the impedance characteristic of the high-frequency cable. Low-loss coaxial cable is available for such service and was used on the Boulder lines. The cable used has approximately 35 times the high-frequency losses of the phase-to-phase primary circuit channel of the same length.

Special attention must be paid to the type and arrangement of the connecting cable. It can be the source of tremendous losses under certain adverse line conditions if not properly connected. With the cable arrangement shown in figure 2, the secondary windings of the

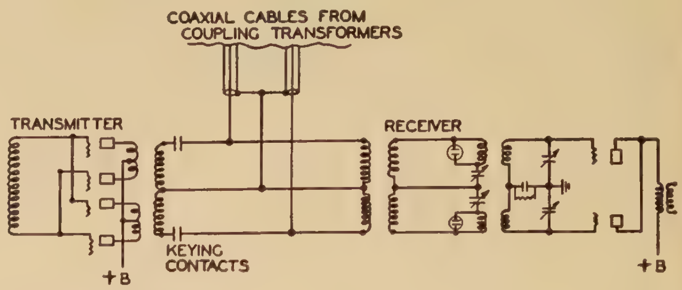


Figure 4. Schematic arrangement of connections of the secondary coaxial cables to the transmitter and receiver circuits

coupling transformers are connected in series and the power from the transmitter is sent over a single cable. Such a connection is satisfactory under normal line conditions, but a large increase in losses occurs if the power conductor of the high-voltage line should break near the coupling capacitors. The coupling transformer associated with the broken line conductor would then have an open-circuited secondary winding, which acts as a high impedance in series with the transformer winding associated with the good line. Hence, the large portion of

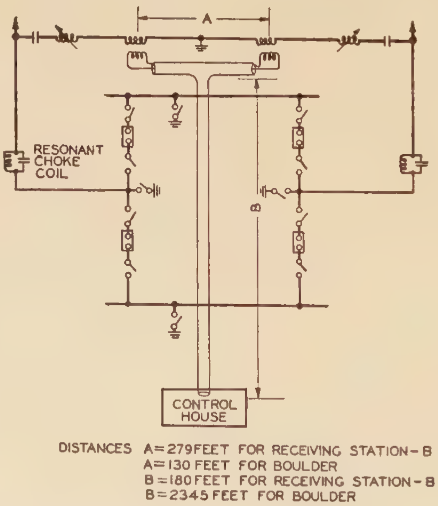
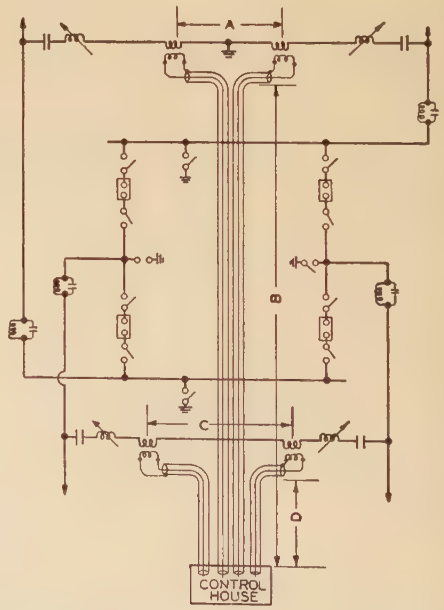


Figure 5. Boulder-Los Angeles lines—terminal stations

Layout of stations—single-line diagram. Shows lengths of high-frequency cable necessary to connect indoor transmitter-receivers to lines

the transmitted voltage appears across the transformer where it can do no good. The Boulder line tests showed that, with the line broken, the loss is 14 decibels greater than under normal conditions with the average distances as shown. The cross-tie portion of the cable also may approach parallel resonance (see equivalent circuit of figure 2) with the inductance of the coupling transformer. Resistors could be used to parallel the coupling-transformer primary-circuit winding and thus reduce the impedance of the open-circuited coupling transformer but this would increase the losses during normal line conditions.

Figure 3 shows the desirable connections of cable circuits. The losses under both line-open and line-short-circuited conditions are effectively reduced. Under the line-open or line-short-circuited condition of the Boulder lines, the output



	A	B	C	D	
DISTANCES	352	520	269	80	FOR VICTORVILLE
	326	520	243	80	FOR SILVER LAKE

Figure 6. Boulder-Los Angeles lines—intermediate switching stations—layout of stations

Single-line diagram shows lengths of high-frequency cable necessary to connect indoor transmitter-receivers to lines

power is reduced only one-half, representing an additional loss of 3 decibels instead of 14 measured with the cable arrangement of figure 2. Each line of the double phase-ground transmission circuit (see figure 4) is independent of the other except for slight changes in the regulation of the transmitter, since each half of the circuit operates independent of the other but from a common power supply. The input circuits into the receiver are also divided into two transformers and input tubes, so that changes on one line will not be seriously reflected into the other or affect the tuning on the working half.

The Boulder Line Characteristics

In measuring the carrier transmission losses on the lines using cable connections of figure 2 at the intermediate stations and of figure 3 at the end stations, some interesting loss characteristics were recorded. (See figures 5, 6, 7, and 8.) First, with the high-voltage lines continuous throughout but with no by-passes in the circuit, the loss at 60 kilocycles was 20 decibels. This loss was measured from end to end and the value 3.33 decibels in figure 8*A* was obtained by dividing the total loss by six, it being assumed that the loss in each section is the same. The lines are approximately 270 miles in length and the calculated loss is only 4.43 decibels. This gives a ratio of measured to calculated losses of approximately five to one (see appendix). Previous tests reported[1] on lower-voltage single-tower systems have not greatly exceeded a 2.5 to 1 ratio of actual to calculated losses. The additional loss may be due to the large spacing between power phases (approximately 265 feet) as compared to distances of the phase conductors to ground and the overhead ground wires. The distance is great because the carrier channel uses the *B* phase of the north line and *C* phase of the south line.

With the by-passes connected in the circuit and the lines energized throughout, the over-all carrier transmission loss increased to 24 decibels. Since the line measured 20 decibels the additional loss of 4 decibels divided by 12, the number of coupling units, gives 0.33 decibels as the equivalent loss per coupling unit. See figure 8*B*. The loss per by-pass was calculated to be 3 decibels. The difference is due to coupling to the other unchoked phases, which forms a parallel circuit to the by-pass equipment. (See figure 9.)

As circuit breakers are opened, the parallel paths through the other unchoked phases are interrupted and the over-all losses increase. The unused phase wires would not affect transmission if the current in them were zero. The

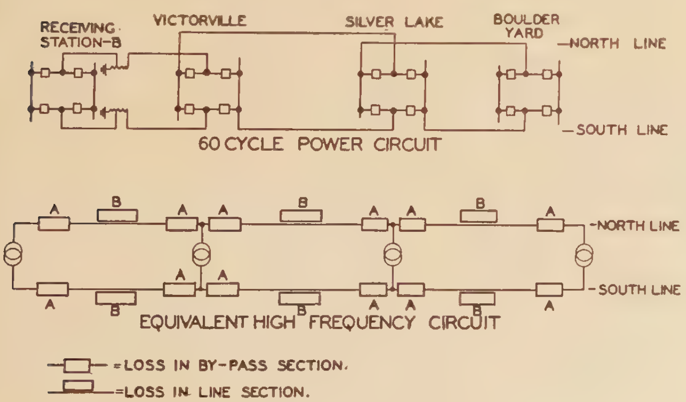


Figure 7. Single-line power and high-frequency circuits—Boulder - Los Angeles transmission line

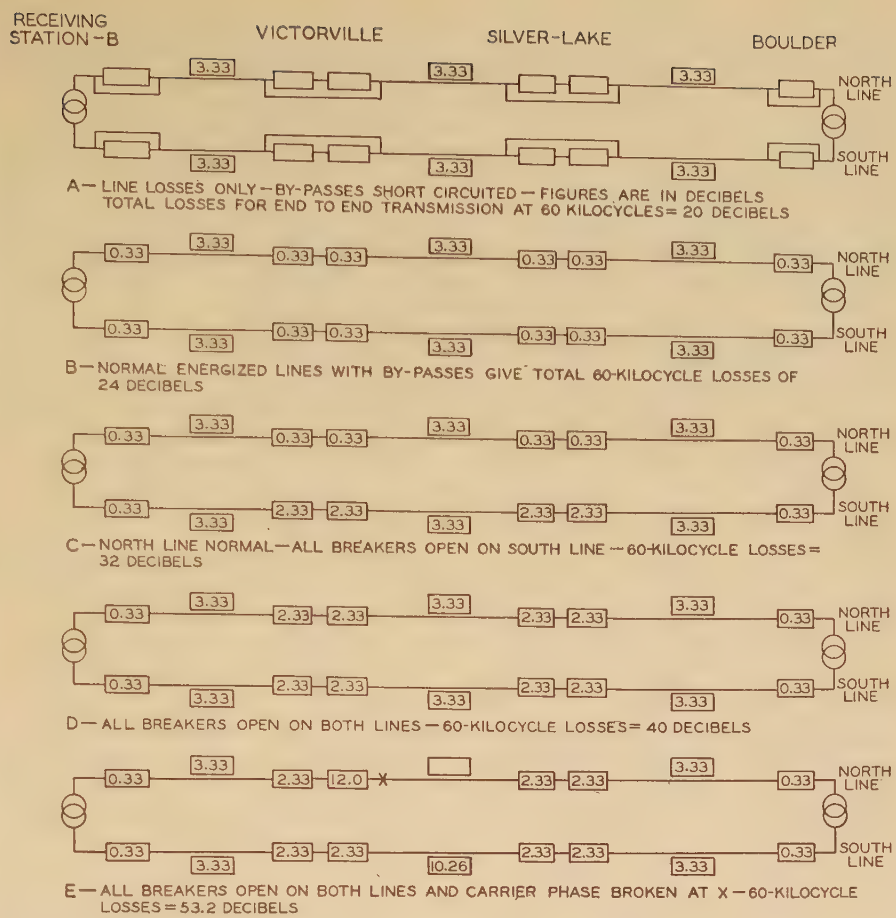


Figure 8. Schematic layout of Boulder-Los Angeles transmission lines showing approximate distribution of carrier-current transmission losses under various line connections

transmission line transpositions are ineffective at 60 kilocycles because of the unbalanced loadings. An unbalance occurs because the terminating impedances to ground on the unused phases are not the same at 60 kilocycles since choke coils used in these phases are tuned to different frequencies. This unbalance makes the by-pass losses lower (see figure 8*C*) on the closed line side than on the open breaker side where all transmission is through the by-pass equipment. Where a phase wire of each line is used, the opening of one line only increases the loss to 32 decibels. Dividing this increase of 8 decibels among the four south line by-passes affected gives 2.33 decibels total loss per coupling unit The total loss per by-pass (four coupling units) is now increased to 5.33 decibels

When breakers of both lines are opened, both sides of the transmission channel are affected, and the loss increases by another 8 decibels. This additional loss is divided by four and the result added to

1. For all numbered references, see list at end of paper.

by-passes at Victorville and Silver Lake. Tests showed that changes in output at Los Angeles and at Boulder were not changed appreciably by opening breakers at these points. The total loss at a switching station is 9.32 (four times 2.33) with all line breakers open. With one breaker opened at either switching station, an additional loss of 4 decibels was measured. Figure 8*D* gives losses for lines when all carrier power is transmitted through all coupling devices and cable circuits connecting these devices.

These changes do not appreciably change the impedance matching of the cable circuits to the line.

With all breakers open and one carrier phase conductor broken, the total loss increases to 53.2 decibels from end to end. In this case, the loss is increased 13.2 decibels. Tests made at Victorville gave a loss there of 12 decibels when line conductor was broken. The additional transmission loss encountered when the line was broken at Victorville was calculated from the change in voltage readings at Victorville under the two conditions of line normal and line broken. (This is shown in figure 8*E*.) Neglecting small increase in losses at Silver Lake, (measurements showed that opening line at Victorville does not appreciably change losses at Silver Lake) the line-to-ground loss for the 90 miles from Victorville to Silver Lake is 10.25 decibels. The loss per mile phase to ground is 0.114 decibel. Of this value 0.037 decibel (based on measured value of 20 decibels for 270 miles) is in the line and 0.077 decibel in the ground circuit.

With cable connections at Victorville and Silver Lake unbalanced (see figure 2) the over-all by-pass losses are three decibels higher than with balanced cable circuits as shown in figure 3. The total loss is 37 decibels, with all line breakers open, as compared to 40 decibels with unbalanced cable circuits.

For the case where line conductor is broken on north line between Victorville and Silver Lake, figure 8*E*, the total losses are 5 decibels less or 48.2 decibels, as compared to 53.2 decibels with the cable circuits unbalanced.

Ground switches are connected inside of the resonant choke coils at each station. Therefore, no transmission difficulties are encountered when ground switches are closed. In fact, the losses show a slight decrease for each ground switch closed.

Special attention should be paid to dividing the carrier transmitter and receiver into parts in such a manner that trouble condition on one phase-to-ground primary circuit will not materially affect the operation of the other half.

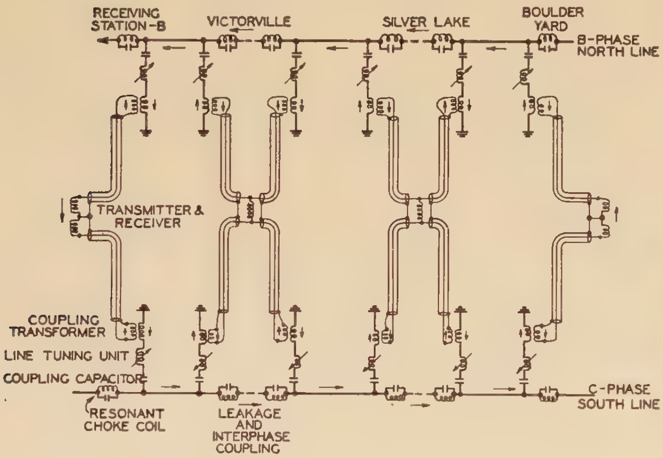


Figure 9. Carrier-current circuit

Primary and secondary arrows show instantaneous current values throughout system. Proper phasing is necessary to get leakage and interphase coupling current to add in phase with current through by-pass

The Carrier Transmitter

The supervisory-control transmitter on the Boulder lines consists essentially of an oscillator, buffer, and power amplifier with a normal output rating of 400 watts. To obtain the best results using the phase-phase-ground primary connections, the amplifier circuit is arranged with two push-pull outputs of 200 watts each. These are connected through independent transformers to the cables of the secondary circuits (figure 4). The plate current is zero except when it is being keyed by the supervisory control equipment.

The Receiver

A heterodyne receiver is used with a beat frequency of 600 cycles or more from zero beat. The input, for double-circuit reception, consists of two input transformers (see figure 4) with series tuned circuits on the secondary side and parallel tuned circuits on grids of the input tubes. The coupling between the two sides of the receiver input circuit is low. Thus grounds or open line conductors do not change the tuning on the unfaulted side of the circuit.

Conclusions

To overcome line noise, the minimum power received for satisfactory operation at any point should be ten milliwatts above line noise level.

For greater interferences, such as that caused by arcs, more received power is necessary or special means are required to prevent altering of coded signals.

Figure 10. View of double tower construction used for approximately 78 per cent of line length

Note distance between lines and construction of towers. The center conductor passes through the tower. The conductors are rotated so that one phase wire goes through the tower for one-third of the line length

On double-circuit lines, phase-phase-ground primary connections are desirable because of greater reliability.

The cable arrangement of the secondary circuits should be balanced to the separate transformers of the transmitter and receiver. This is the equivalent of

two independent phase-ground systems.

High-frequency losses over the 287-kv Boulder-Los Angeles power lines measured approximately five times those calculated, using the present accepted methods for such calculations (see appendix). Previously reported tests gave a maximum of approximately 2.5 times. It is apparent that changes in the present working formulas will be necessary.

Figure 11. View of single-tower construction used for approximately 22 per cent of line length

The phase wires of the two lines are relatively close with none passing through the towers

Figure 12. One corner of an intermediate switchyard showing outdoor line-tuning units. Underground coaxial cables connect the carrier circuits to the indoor transmitter-receiver sets

Appendix

Calculations of Line Losses

The high-frequency resistance for tubular conductors as given in Bureau of Standards Circular No. 74, page 301 is

$$\frac{R_{ac}}{R_{dc}}=10\sqrt{2}t(0.01071\sqrt{f})=0.1514t\sqrt{f} \qquad (1)$$

where

$t=$ conductor wall thickness in centimeters
$f=$ frequency in cycles per second
$\frac{R_{ac}}{R_{dc}}=$ ratio of a-c to d-c resistance

At 60 kilocycles, and wall thickness of 0.278 centimeters.

$$\frac{R_{ac}}{R_{dc}}=0.1514\times0.278\sqrt{60{,}000}=10.32$$

The d-c resistance of conductor (512,000 circular mils) is 0.22 ohms per loop mile. Hence the 60-kilocycle resistance for conductor is

$$R_{ac}=10.32\times0.22=2.27 \text{ ohms per loop mile}$$

The approximate formula for the real part of the attenuation constant is as follows:

$$a=\frac{R}{2Z_0}+\frac{CZ_0}{2} \qquad (2)$$

for the real part of the propagation constant where

$R=$ resistance in ohms
$G=$ leakage conductance in ohms
$Z_1=$ surge impedance $=$ 600 ohms phase to phase
$a=$ attenuation constant

For high-voltage open-wire lines $G=0$ and (2) reduces to

$$a=\frac{R}{2Z_0} \qquad (3)$$

In terms of current, for long lines

$$I_x=I_0\epsilon^{-ax}$$

$$\text{DB}=10\log_{10}\frac{I_0^2}{I_0^2\epsilon^{-2ax}}=10\log_{10}\epsilon^{2ax}$$

$$=20ax(0.4343)=8.686ax$$

Substituting from (3)

$$\text{DB}=\frac{8.686R}{2Z_0}=\frac{4.343R}{Z_0}\text{per unit length} \qquad (4)$$

In this case the a-c resistance is 2.27 ohms per loop mile.

$$\text{DB}=\frac{4.343\times2.27}{600}=0.0164 \text{ per loop mile}$$

For 270 miles of line, the loss as calculated is 4.43 decibels.

When transmitting phase to ground, the calculated losses are as follows:

The ground circuit can be along a copper circuit consisting of two quarter-inch-diameter copper wires for which the 60,000-cycle resistance is 2.55 ohms per mile as calculated by Bureau of Standards formulas. For this value of resistance the loss is

$$\text{DB}=\frac{4.343\times2.55}{300}=0.037 \text{ per mile}$$

In this case $Z_0=300$ ohms as measured. The total line-to-ground transmission loss is $0.0164+0.037=0.0534$ decibels per mile.

References

1. C. A. Boddie. IRE *Transactions*, June 1927.

2. A Self-Checking System of Supervisory Control, M. E. Reagan. AIEE Transactions, volume 57, 1938, pages 600–05 (October section).

3. Symposium on Operation of the Boulder Dam Transmission Line—Carrier Current Equipment, J. D. Laughlin. AIEE Transactions, volume 58, 1939, pages 147–51 (April section).

Discussion

W. A. Lewis (Cornell University, Ithaca, N. Y.): There are two points in connection with this paper that I would like to augment.

The discussion points out the serious effects on the operation of the carrier-current supervisory equipment caused by arcing at the opening and closing of disconnecting switches and circuit breakers. Those engineers who are concerned with the operation of carrier-current relaying equipment may have some fears regarding the effects of similar arcing on the performance of carrier-current relaying equipment. However, the large number of satisfactory installations of carrier-current relaying suggests that such fears are not warranted. Tests made a number of years ago perhaps indicate why this is so. It was found at that time in tests made at low voltage that a flaming arc in air did not produce appreciable amounts of high-frequency transients in the carrier-frequency range, whereas spark discharges, as are obtained by the opening of disconnecting switches which open only a small amount of charging current, and also arcs in circuit breakers which are very quickly extinguished both produce large amounts of high-frequency energy which may operate the carrier-current receivers of the relaying equipment. Fortunately, the necessity for the receiver responding only to the carrier-current energy transmitted by the transmitter at the opposite end of the line is only critical for the duration of the fault, and after proper circuit breakers have been selected, and have started to open, it is unimportant that the carrier-current receiver may be momentarily energized. In the

event that circuit breakers or disconnecting switches are opening at the moment a fault occurs on an adjacent line section, it is conceivable that the carrier energy from the operation of the circuit breaker or disconnecting switch may interfere with the relay operation, but in any event it is probable that the most serious effect will be a short delay in the operation of the line relays.

The method of computing the transmission loss is described in the paper, and it may be seen that the only losses considered are the high-frequency copper losses in the copper conductors actually involved in the circuit. From the tests, it is evident that there are additional losses which are not taken into account by this method of calculation. From the physical standpoint the supervisory-control circuit consists of a single-turn loop, one side of which is the *B*-phase conductor of the north line, and the other side is the *C*-phase conductor of the south line, separated by 365 feet from the other side of the loop. It may readily be visualized that this loop forms the primary circuit of an air-core transformer, the secondary of which consists of eddy-current paths in the earth immediately below the carrier transmission circuit. It is to be expected that eddy currents would be produced in the earth, and their losses would appear as transmission losses to the carrier-current circuit. Also, there will be some radiation, and some current induced in the other neighboring conductors. All of these losses will add to the conductor copper loss in the carrier channel. For the calculation of ground-return circuits at power frequencies, the formulas developed by J. R. Carson, or some modification of them, have been used with considerable success. Investigation of the underlying premises indicates that theoretically, at least, these formulas are applicable to the carrier frequencies in the range covered by this installation. It would be extremely interesting, therefore, to calculate the losses of this circuit by means of the Carson formulas, and determine if these formulas give an adequate representation of the losses. In any event it is to be expected that such calculations would give a much closer approach than is obtained when only the conductor copper losses are included.

Fred B. Doolittle (Southern California Edison Company, Los Angeles): Appreciation is due the authors for making available the information contained in their paper entitled "Carrier Current Losses Measured and Interference Minimized on Boulder-Los Angeles Transmission Lines". It is to be hoped that further study will reveal the reason for the five-to-one ratio between measured and calculated transmission losses.

While the secondary circuits used by the authors were different than those used by the Southern California Edison Company on the application of carrier-current protection to the 96-mile Gould-Magunden 220-kv transmission line and while the line construction is also different it would hardly seem that these factors could account entirely for the discrepancy which appears to exist between phase-phase and phase-ground transmission losses on the two lines. The received power phase to phase being 3.25 times that phase to ground as reported for the Boulder line is a much greater difference than found on the Gould-Magunden line. Tests on the latter in 1932 indicated phase-to-ground transmission was about 70 per cent as efficient as phase-to-phase.

The ingenious scheme described in the paper for blocking the receiver during the occurrence of high-voltage switching interference is of course well suited to the purpose for which it is used. However, it should not be used where the carrier signal is for the purpose of preventing the operation of tripping relays for transmission line protection. When, in 1932, it was observed that switching arcs on the Edison 220-kv system produced interference of sufficient magnitude to flashover all of the protective gaps associated with the carrier-current coupling equipment it was first thought that it would be impracticable to use sufficient carrier-current power to override interference of such magnitude. However, further experimentation demonstrated that such was not the case and that a $7^1/_2$-watt carrier-current transmitter over a 30-mile line could produce three or four times as much average detector plate current in a properly biased receiver as was produced by the interference created by operation of a 220-kv disconnecting switch. This fact made possible the interlocking type of carrier-current protection which was placed in service on the East Gould-Laguna Bell 220-kv line in April 1933.

While use was made of the fact that comparatively small amounts of carrier power would override violent interference, the reason therefor was not definitely proved until some months later when, by means of a cathode-ray oscilloscope, the wave form of the detector grid voltage was viewed. This wave form under switching interference was that of a damped oscillation in the resonant circuit of the receiver produced by shock excitation, twice each cycle of the power frequency when the instantaneous power voltage reached sufficient magnitude to jump the switch gap. The maximum magnitude of the damped oscillation could be controlled by the setting of the protective gaps in the carrier-current coupling circuit. Of course the continuous wave received from the remote transmitter was not damped and produced a higher average detector grid voltage than the series of damped oscillations caused by the interference.

J. D. Laughlin, W. E. Pakala, and M. E. Reagan: Doctor W. A. Lewis points out that experience has shown that interference from breakers and disconnecting switches does not produce faulty operation on carrier-current relaying systems. It is fortunate that interference power level in the carrier-frequency spectrum is sufficiently low to enable us to use less than 50 watts of power for carrier-current relaying and receiver sensitivities so low that interference has no effect on the receiver relays. Interference, however, should be considered, and too low carrier power levels should not be used. For carrier loss calculations it has been general procedure to calculate copper losses as in the paper, and then use factors obtained by experience on high-frequency transmission over power lines to obtain line losses for the design of equipment. We have made calculations taking into consideration the losses in the ground circuit and have obtained loss value of 30.4 decibels (line only) for earth resistivity of ten ohms per meter cube.

Fred B. Doolittle has brought up a point which was not made sufficiently clear in the paper. One phase-to-ground loss was measured as 26 decibels and the phase-to-phase loss as 20 decibels. The statement made in the paper that the phase-to-ground loss is 3.25 times the phase-to-phase loss is based on a calculated value, assuming that all ground current is concentrated in the counterpoise wires.

The effect of interference from switching on the detector plate meter and receiver relay is not, as pointed out by Mr. Doolittle, as serious as would be expected from observation of breakdown of the protective gap. High crest voltages of only a few microseconds duration have no effect on the receiver relay, which is relatively a low device connected in series with a vacuum tube which can act as a current-limiting device. However, interference of long duration, such as from the 287-kv disconnecting switches, will pick up the receiver relays unless some means is provided to desensitize the receiver during interference time. The system described in the paper requires carrier transmission for 270 miles at the time interference is transmitted for much shorter distances.

Hydrogen-Cooled Turbine Generators

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ONE of the most radical innovations in the design of electrical machinery in recent years has been the adoption of hydrogen cooling for large turbine generators. Now that a number of the large hydrogen-cooled units are in operation, it would seem timely to review the experience gained in building and operating this new-type equipment.

The developments leading up to the design of the present large machines may be summarized briefly as follows. In 1923, Max Schuler of Germany took out an American patent covering the cooling of rotating electrical machines with hydrogen gas. The company with which the writers are associated took out a license under this patent in 1924 and began development work on a suitable sealing device to prevent escape of gas along the shafts of the machine where they come out of the gas-tight housing. The shaft sealing glands, as they shall be referred to hereafter, were developed in essentially their present form in 1926. Work was then started on a 7,500-kva 3,600-rpm turbine generator with hydrogen cooling, and this was built and tested in 1928. A second machine of the same size was built and tested in 1930. The results of these tests are covered in a previous paper by one of the authors.[6]

During the years 1930 to 1936, no commercial applications of this new method of ventilating machines were made largely because of the small number of machines sold during that time. Early in 1936, there developed a considerable demand for large 3,600-rpm high-pressure topping units to be used to modernize old stations. The increased output from a given size machine with hydrogen cooling permitted units to be built in ratings up to 50,000 kw with the materials and experience then available. Since 1936, over 580,000 kva of hydrogen-cooled turbine generators have been sold representing 11 units, the largest of which is rated 81,250 kva at 80 per cent power factor at 3,600 rpm. One unit rated 75,000 kva at 80 per cent power factor at 1,800 rpm has been in operation for some time. All the other units are designed for a speed of 3,600 rpm. The smallest unit is rated 37,500 kva at 80 per cent power factor at 3,600 rpm.

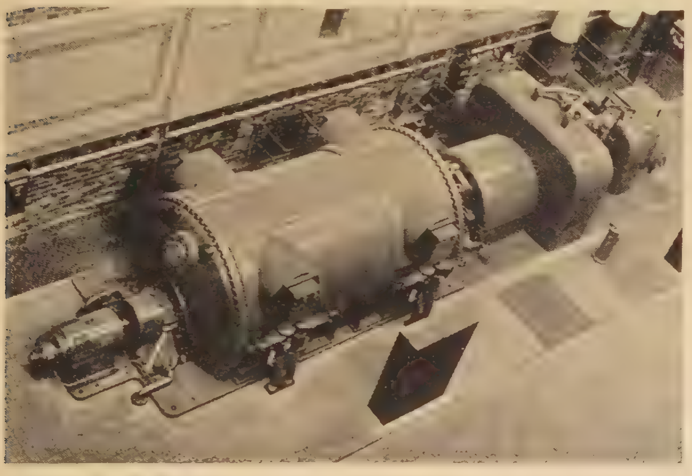

Figure 1. A 53,000-kw hydrogen-cooled generator and turbine installed at Waterside station, New York City

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M. D. Ross is section engineer, a-c generator section, and C. C. Sterrett is electrical design engineer, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.

6. For all numbered references, see list at end of paper.

Advantages of Hydrogen as a Cooling Medium

The advantages of hydrogen cooling have been covered fully in a number of papers. It is sufficient, therefore, only to state briefly the principal points here, as follows:

1. Reduced windage, friction, and ventilating losses, because of the low density of the hydrogen gas. The ventilating losses are proportional to the gas density. Full load efficiency of the generator may be 0.6 per cent or more higher than for the corresponding air-cooled machine.

2. Increased output per unit volume of active material, because of the high heat storage capacity and thermal conductivity, and heat transfer coefficients of hydrogen. This advantage of hydrogen cooling makes it possible to build turbine generators for higher ratings than are possible with air cooling.

3. Reduced maintenance expense, because of the freedom from dirt and moisture.

4. Increased life of the insulation on the stator winding, because of the absence of oxygen and moisture in the presence of corona.

5. Reduced windage noise, because of the low density of the gas.

Description of Hydrogen-Cooled Generator

Hydrogen-cooled generators are designed so as to be "explosion-safe"; that is, all equipment is built to withstand a hydrogen explosion without damaging life or property. During normal operating procedure, an explosive mixture of hydrogen and air will not exist in the generator; however, in order to take care of faulty operation or unforeseen conditions, a suitable control and signal system is provided to warn when operation is approaching dangerous conditions. The operating hazard of a hydrogen-cooled generator is no greater than that of an air-cooled machine. Hydrogen is usually associated with dangerous explosions, but it is important to note that oxygen is required in considerable quantity before hydrogen will burn; explosive mixtures of air and hydrogen contain from 5 to 70 per cent hydrogen by volume, various authorities differing a small amount on these figures. The purity of the hydrogen in the generator is maintained above 95 per cent hydrogen, well above the upper explosive limit. The operating procedure together with the control system make a hydrogen explosion a remote possibility.

The construction features of a hydrogen-cooled generator are shown in figures 2 and 3. The generator frame and end domes are fabricated from steel plate which is rolled and welded to form the required shapes; the generator shell being cylindrical and the end heads being dome shaped as these shapes will best withstand the high internal pressure which would result from an explosion. On the basis of the most favorable mixture for an explosion, the pressure developed inside the machine enclosure

would not exceed one-half the maximum theoretical value, because of the large heat-storage capacity of the machine and the exposed surfaces of the large mass of the parts of the machine. Analysis and experience indicate that the maximum actual explosion pressure will not exceed 85 pounds per square inch; consequently, it has become accepted practice to design the housings of hydrogen-cooled machines to withstand an internal pressure of 100 pounds per square inch without failure. Frame welds are tested individually for gas leaks and the complete generator frame and end domes are tested for leaks with water pressure at 75 pounds per square inch. The joints in the generator frame and end head assembly which must be gas-tight are made with suitable gaskets and cement.

Armature laminations are built into the frame after the water pressure test. The stator laminations are varnished and baked, and then the stator coils are installed in the stator slots, the coils being transposed and stranded to reduce eddy currents to a minimum. The generator main leads are brought out through gas-tight capacitor-type bushings which are bolted to the generator frame. Nine armature temperature detectors are located in the armature windings, and four temperature detectors are located in the gas passages, one at the inlet and outlet of each gas cooler.

The generator rotor is made from a single forging in which slots are machined to receive the rotor winding. Ventilating passages are provided under the coil slots and in the end windings to secure efficient ventilation of the rotor. The rotor end turns are supported by coil retaining rings which are shrunk on the rotor body.

Hydrogen-cooled generators are equipped with finned-tube-type gas coolers, located above or below the stator core; in either case, the gas coolers are located so that the tubes run crosswise in the generator frame. The nozzle end of the gas cooler is bolted solidly to the generator frame, while the rear end is permitted to move freely with temperature changes. The finned tubes are supported so as to eliminate vibration. The cooler tubes may be cleaned without losing gas from the generator housing by removing the nozzle and rear end water boxes, a flexible rubber diaphragm on the rear end between the generator frame and cooler serving to keep the gas in the generator. The gas coolers are installed so as to be readily accessible, and so as not to weaken the generator cylindrical shell.

The hydrogen-gas ventilating circuit is shown in figure 2. A propeller-type blower, consisting of a steel hub with aluminum blades, is mounted on each end of the rotor, and these circulate the hydrogen through the rotor and stator, where it picks up heat, and then through the finned-tube gas coolers, where the heat is transferred to the cooling water in the tubes. The cooling gas may complete 30 to 40 such circuits in a minute. The interchange of cooling gas between the two ends of the generator is very small, so that both coolers are required when the generator is running. Hydrogen-cooled generators are designed to carry at least 75 per cent rated load, with normal temperature rises, running air cooled.

Manholes in the end domes, and portlights on the side of the generator are provided so as to permit observation of the internal machine parts without disassembling the generator end domes.

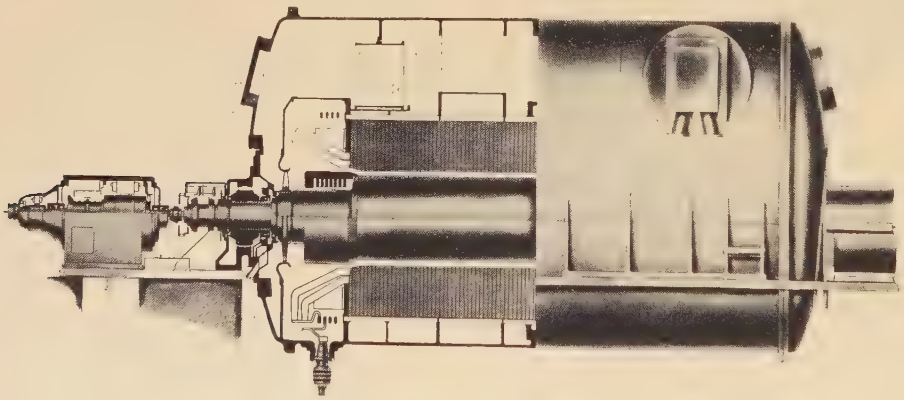

Figure 2. Longitudinal section view of a 53,000-kw hydrogen-cooled generator with direct-connected exciter

The generator tool-steel collector rings, spiral grooved to improve commutation, are located outside the generator bearings. The main and pilot exciters are driven at the same speed as the generator rotor, and have one or two bearings, depending on the size of the exciter. Two-bearing exciters are flexibly connected to the generator rotor. The special floating-type commutator on the exciter provides satisfactory operation at 3,600 rpm.

Description of Generator Shaft Gland Seals and Oil System

A hydrogen-cooled generator requires shaft gland seals on each end of the generator rotor to keep the hydrogen gas in and the air out of the generator housing. The shaft gland seal details are shown in figure 4. The special feature of the shaft gland seal is the sealing rings which are located in grooves in the seal member and are fitted close to the shaft and are free to move with the shaft radially, but are pinned so that they cannot rotate with it. These sealing rings reduce the flow of oil to a relatively small quantity, approximately one gallon per minute to each seal. Gland seal oil is supplied at approximately five pounds per square inch behind the sealing rings, and this oil flows out to the rotor shaft through radial holes in the sealing rings. The oil then flows both ways from the center of the sealing rings, part toward the air side of the seal and part toward the hydrogen side of the seal. As long as gland seal oil pressure is maintained, hydrogen gas will not escape along the shaft even if the gas pressure approaches that of the hydrogen gland seal oil pressure. The gland seal oil leaving both the air and hydrogen sides of the seals is collected and returned to the gland seal oil reservoir. A very small amount of gland seal oil is lost to the main bearing oil at the shaft gland seals.

The relation of the various elements which comprise the complete gland-seal-oil-supply system is shown diagrammatically in figure 5. The gland seal oil that is drained from the hydrogen side of the sealing rings flows by gravity to the defoaming tanks, where the foam is permitted to settle out, before the oil is returned to the gland-seal-oil reservoir. This defoaming tank also acts as a valve in case of an explosion in the generator as sufficient oil is provided in the tank, and the oil and gas passages are of such relative size, that it cannot be emptied in the 10 to 15 seconds in which the machine pressure might be above atmospheric pressure. This prevents driving hydrogen gas into the main and gland oil reservoirs under such conditions.

The gas pressure in the generator and

defoaming tanks is balanced by a column of oil in the loop seals located beyond the defoaming tanks.

The gland-seal-oil reservoir is integral with the main oil reservoir, but the oil interchange between these two tanks is very small. Sufficient oil from the main-bearings oil-return line is admitted to the gland-seal-oil reservoir by the float-controlled valve to make up that gland seal oil that is lost to the bearing system at the shaft gland seals.

It is necessary to remove the gas and moisture from the gland-seal-oil supply by a vacuum-treating process, otherwise the oil leaving the hydrogen side of the shaft gland seals would liberate gas and moisture in the generator housing and this would reduce the hydrogen purity. In the vacuum-treating unit the gland seal oil is subjected to a vacuum of one inch mercury absolute or less. As the oil is sprayed into the vacuum, the water flashes into steam, and the entrained gas in the oil expands and bubbles out of the oil. The vacuum pump draws these gases out of the vacuum tank, discharging the gases out the vent to outside, and draining the water out of the separator tank just beyond the vacuum-pump exhaust. The vacuum-treating unit is so arranged that it may be segregated from the gland seal oil supply system for a limited time for inspection and maintenance without materially affecting the operation of the generator. Continued operation without the vacuum-treating unit would result in air being liberated into the generator housing and the addition of hydrogen would be required to maintain the hydrogen purity in the generator.

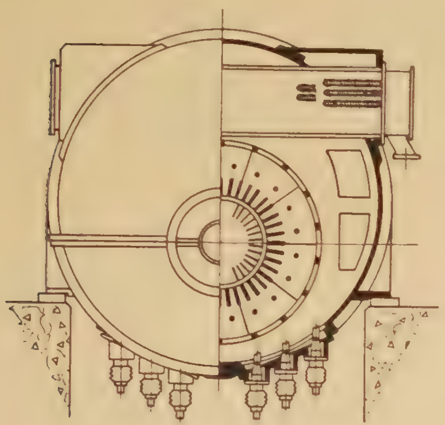

Figure 3. End section view of a 53,000-kw hydrogen-cooled generator showing the gas-cooler arrangement

The shaft-gland-seal-oil supply is normally secured by an oil-turbine-driven oil pump, using high pressure oil from the impeller on the turbine shaft for driving power. If this pump should fail, a pressure-operated Mercoid switch operates to start an electric-driven seal oil pump. Also an emergency connection is provided between the main bearing supply system and the gland seal oil supply system, whereby a diaphragm-operated regulating valve operates to admit bearing oil pressure to the gland-seal-oil system in case the pressure drops to approximately three pounds per square inch. Shaft gland seal oil is thus guaranteed so long as the generator rotor is running. When using the main bearing oil for the shaft gland seals through the emergency connection, it is necessary to add hydrogen from time to time to maintain the hydrogen purity. The vacuum-treating unit should not be operated when the emergency seal supply system is used.

An important feature of the gland-seal-oil supply and main-bearing oil supply systems is the ventilating blowers which are direct connected to the gland-seal-oil supply pumps. These ventilating blowers create a vacuum of about two inches of water pressure in the gland-seal-oil and main oil reservoirs, in the main-bearing drains, and in the bearing pedestals. All of the bearing drain lines are designed so as to flow partially full of oil, leaving a ventilating passage. There is, therefore, a flow of ventilating air through the labyrinth oil sealing strips at the bearing pedestals, which air flows through the partially full oil drain lines to the main oil tank, thence to the gland-seal-oil reservoir, and through the ventilating blower to the vent to outside. Hydrogen accumulation in the pedestals and drain lines, and oil tanks, is thus eliminated.

Gas Control System for Hydrogen-Cooled Generator

The gas control system is shown schematically in figure 6. The principal functions of the gas control system are to provide means for maintaining the hydrogen in the generator within the proper purity, pressure, temperature, and moisture limits; and to provide means for filling and scavenging the generator housing with gas; and to warn the operator when operating conditions are not normal.

Figure 6 illustrates the gas control system during normal operating conditions. The hydrogen pressure in the generator housing is automatically maintained at approximately 5 to 10 inches of water pressure in order to prevent air leakage into the generator housing. A Mercoid pressure switch energizes the solenoid hydrogen inlet valve when the gas pressure drops to about 5 inches of water pressure. A diaphragm operated relief valve regulates the upper pressure limit by exhausting gas to atmosphere at approximately 20 inches of water pressure. A push button is located on the gauge board for manually operating the solenoid hydrogen inlet valve to increase the hydrogen purity, the excess pressure resulting from the hydrogen admission being released by the diaphragm-operated relief valve.

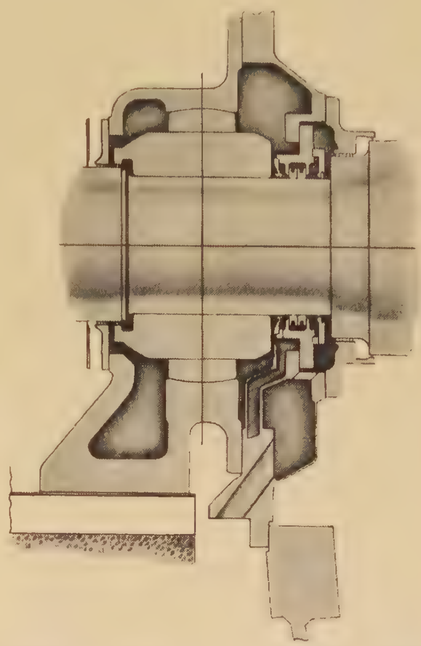

Figure 4. Section view of pedestal bearing and shaft gland seal for a hydrogen-cooled generator

A machine gas pressure gauge, containing high and low alarm contacts, is located on the gauge board. Also another pressure gauge is located adjacent to the manual gas-supply bottles so that the operator can observe the machine gas pressure during the scavenging and filling operations. Both of these pressure gauges are of a special design capable of withstanding the explosion pressure, although the full-scale range is only 0 to 60 inches of water pressure.

The purity of the hydrogen gas in the generator housing is indicated on the gauge board by a "density meter" which gives a direct check on the hydrogen purity as the density of hydrogen is much less than the density of air. The density-meter blower runs at constant speed, being driven by a lightly loaded induction motor, and samples the machine gas continuously. The pressure developed

by this blower is directly proportional to the density of the gas, and this pressure is used to actuate the density meter on the gauge board which is merely a 0 to 20 inches of water differential pressure gauge. The density-meter dial is graduated 0 to 150 per cent density, 100 per cent density being arbitrarily taken as the density of air. The density meter may be calibrated by closing the two valves which connect the blower to the generator, and opening the two air sampling valves. The orifice needle valve which connects the two pressure lines leading to the density meter may then be adjusted until the density meter indicates 100 per cent density. The density meter blower can then be connected so as to sample and indicate the machine gas density. Contacts are provided for indicating high gas density, and failure of the density meter blower. A fan pressure gauge is provided on the gauge board which indicates the pressure developed by the fans on the generator rotor, and serves as a check on the density meter.

A bottle-pressure gauge is provided on the gauge board with high and low alarm contacts to indicate respectively that the gas reducing regulators at the automatic hydrogen supply bottles have failed or that the gas bottles are empty and require replacement. Also an indicating thermometer with a high alarm contact is provided on the gauge board to indicate the gas temperature in the generator housing.

Hydrogen-cooled generators require a small gas dryer which removes a small amount of moisture from the gas in the generator housing, and thus keeps the dew point of the cooling hydrogen below the temperature of the gas in the cooler tubes, and prevents condensation within the generator. Hydrogen is circulated through the reactivated alumina dryer by means of the generator fan pressure. At approximately weekly intervals, the dryer is disconnected from the generator and reactivated by heating the activated alumina and blowing room air through the dryer tank, these operations being readily performed by operating valves provided and starting the heater and air blower. The normally blue activated alumina crystals turn gray when full of water, as evidenced by the sight glass on the side of the dryer tank.

Water detector float switches are connected to the low points in the bottom of the generator frame, and these sound an alarm when full of water, indicating water is collecting in the generator.

When operating conditions are abnormal, an alarm is sounded at the gauge board and a signal light indicates the source of the alarm. The following alarms are normally provided on a hydrogen-cooled generator:

1. High gas density
2. Low gas density
3. High gas pressure
4. Low gas pressure
5. High bottle pressure
6. Low bottle pressure
7. High gas temperature
8. Water detector full
9. Gland low oil pressure
10. D-c power supply off
11. Vacuum oil treating unit

The gas supply bottles and operating valves are usually located conveniently under the generator. A manual supply of hydrogen and carbon dioxide is provided for filling and scavenging the generator housing with hydrogen. It is necessary to scavenge the oxygen from the generator housing with an inert gas, such as carbon dioxide (or nitrogen) before introducing the hydrogen into the generator housing to prevent mixing of air and hydrogen. Two volumes of inert gas will reduce the oxygen content to a safe figure for introducing hydrogen. Three and one-quarter volumes of hydrogen are then required to bring the hydrogen purity up to 95 per cent hydrogen. The density meter may be used to check the various gas purities.

During normal operation of a hydrogen-cooled generator the gland seal oil carries air in and hydrogen out of the generator. An air in-flow of one cubic foot requires the addition of 24 cubic feet to maintain the hydrogen purity at 95 per cent. When it is required to remove the hydrogen from the generator housing, approximately three volumes of inert scavenging gas are required to reduce the hydrogen purity to a safe figure for adding air.

Operating Experience

The first unit to be filled with hydrogen went into operation on May 5, 1938. Since that time, four other units have gone into operation with hydrogen cooling. Hydrogen gas used by these machines runs from 20 to 90 cubic feet per day when the generator is running and considerably less when the generator is shut down. Some gas is lost due to variations in machine gas temperature which causes fluctuations in gas pressure sufficient to operate the relief valve. Gas purity remains at well over 95 per cent without adding gas to improve the mixture showing that the infiltration of air with the gland seal oil is quite small.

As in nearly every radically new design, some troubles were encountered at the outset. Shortly after the first unit started up with hydrogen, water was noticed in the water detectors connected to the bottom of the machine. While the quantity was not large, its presence was disturbing. After some investigation, it became apparent that the water

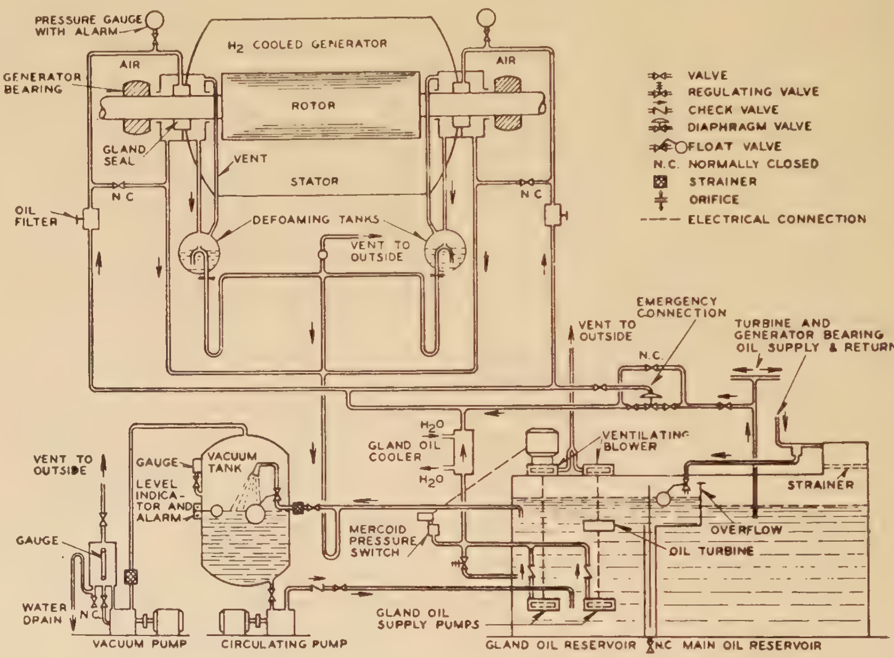

Figure 5. Schematic diagram of the shaft-gland-seal oil-supply system for a hydrogen-cooled generator

in the generator was coming from the gland seal oil. Small quantities of water in the gland seal oil were being evaporated at the shaft sealing glands on the hydrogen side and the water vapor eventually found its way into the generator by diffusion through the gas. When it entered the generator, the moisture content of the gas increased until the dew point reached the temperature of the tubes of the gas coolers. Water then condensed on the cooler tubes and ran down into the water detectors. As originally designed, the shaft sealing glands used oil from the lubricating system without special treatment other than running it through baffles in the gland seal tank to remove air bubbles. Any water that got into the lubricating system was, therefore, likely to be taken over into the generator. To overcome this situation, three changes were made in the machines. A vacuum-treating system was inserted in the gland seal oil system to remove the major portion of the water in the oil pumped to the shaft sealing glands. Additional drains were installed in the sealing glands so that oil coming off the air side of the seals could be caught and kept separate from the lubricating oil and drained back to the gland-seal-oil reservoir. This move practically isolated the gland seal and lubricating oil systems one from the

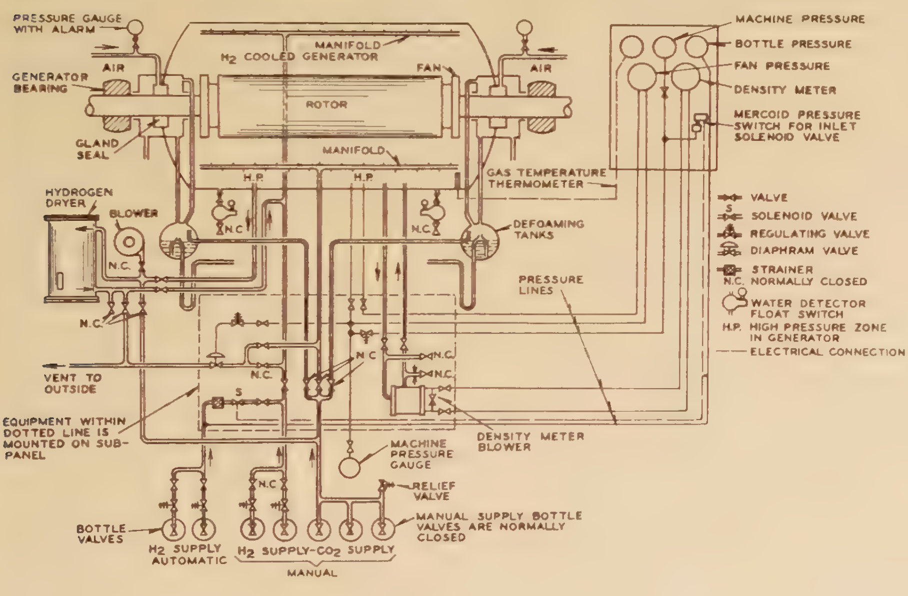

Figure 6. Schematic diagram of the gas control system for a hydrogen-cooled generator

other so that the vacuum-treating system was required to treat the same quantity of oil over and over again rather than to be treating a large amount of oil from the lubricating system.

Tests at the factory on a shaft sealing gland showed that even though the vacuum system reduced the water in the oil to less than 0.003 per cent, a certain portion of this small quantity of water would get into the generator and would in time raise the dew point to the saturation point corresponding to the cooler tube temperature. A small dryer of the activated-alumina type was, therefore, connected into the gas system so that a small portion of the hydrogen would be circulated continuously through the dryer to remove the last traces of moisture that might get into the generator.

These three changes have proved to be entirely satisfactory in keeping water out of the generator. The addition of the vacuum-treating system and the dryer have added very little to the work of the station operators and it should be noted that neither piece of equipment is vital to continuous operation and can be cut out of service at any time for several hours for inspection without affecting the operation of the generator.

One other major trouble encountered was the excessive vibration of the tubes of the gas coolers which resulted in wear of the fins on the tubes where they passed through the tube support plates. As pointed out in a companion paper, the two-pole generator stator is subject to double-frequency vibrations set up by the magnetic field. This vibration is always present in such machines but had not been recognized as important until these large-diameter two-pole machines were built. It was not recognized that a cooler construction suitable for mounting on the foundation of the unit would not be adequate when closely connected to the frame of the generator. As soon as the problem was realized, the solution of adding extra tube-support plates in the coolers to change their vibration periods became apparent. A number of other detail changes were also made and no further trouble from this source has developed.

Exciters

This paper would not be complete without some mention of direct-connected exciters for the large 3,600-rpm units. While some doubts were expressed by the purchasers at the time of buying these large units, concerning the possibilities of trouble with exciters up to 165 kw rating at 3,600 rpm, their operation to date has been entirely successful. A 65,000-kw unit is now on order for which a direct-connected 260-kw exciter will be provided. All the large units have been provided with pilot exciters with armatures overhung on the end of the main exciter shafts.

Conclusion

With operating experience on a number of units and over a considerable period of time at hand, the initial stage of development of hydrogen-cooled generators is passed. There will no doubt be minor difficulties to correct as time goes on, but these will be of no more serious nature than are to be found in air-cooled generators. It will also be possible to simplify considerably the generator and its attendant parts in future machines as greater experience is gained with this type of machine. Cost of supplying hydrogen gas is very low, and it has been the experience in most stations that the additional attention on the part of the operators as compared to that for an air-cooled machine is very small. Hydrogen cooling will probably be adopted more and more for units of 30,000 kw and above where the additional cost of the gas-tight housing and gas control can be justified economically.

The adoption of hydrogen cooling for large machines has enabled the size of 3,600-rpm machines to be pushed up to 81,250 kva at 80 per cent power factor. With further experience, it will no doubt soon be possible to build 100,000 kva, 80 per cent power factor at 3,600 rpm with this method of cooling.

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Discussion

Sterling Beckwith: See discussion, page 38.

S. H. Mortensen: See discussion, page 48.

C. F. Hill and L. J. Berberich: See discussion, page 48.

D. S. Snell (General Electric Company, Schenectady, N. Y.): I wish to compliment Messrs. Ross and Sterrett on the stator-frame construction developed for their hydrogen-cooled generators, which allows the use of somewhat larger and more accessible coolers for given shipping dimensions than practicable with the conventional round frame construction. In our designs, we have preferred the use of four coolers placed lengthwise of the casing, in place of the two-cooler-crosswise arrangement, to permit removal of any one cooler from service without shutting down the machine, and at the same time maintaining uniform temperature distribution in the cooling medium.

The type of shaft sealing gland described in this paper has the advantage over the solid-ring type of seal, constructed integral with the bearings, of requiring a considerably lower oil flow, and thereby reducing the size of the oil-treating equipment. However, it has the disadvantage of having loose parts which may under certain circumstances seize the shaft and be destroyed, and also introduces the possibility of misalignment with the shaft, which is not present with the solid-ring type of seal. While we are using a shaft seal of the floating-ring type with some of our 1,800-rpm hydrogen-cooled generators, we consider the solid-ring type of seal to be preferable with generators of the 3,600-rpm class, since machines of the latter class are more susceptible to vibration difficulties.

In connection with the seal oil supply system described in this paper I would suggest that a slight improvement in the degree of vacuum treatment of the gland sealing oil would result in obtaining an appreciable increase in the percentage hydrogen purity held in the generator casing and would also decrease the amount of moisture entering the casing through the gland seals. I would ask the authors if they do not consider the effectiveness of their vacuum-treating system to be somewhat reduced by the reabsorption of air by the oil in the gland oil reservoir. Tests by F. M. Clark, reported in the *Journal* of the Franklin Institute, volume 215, 1933, page 39, showed that vacuum-treated oil exposed to air in an open vessel absorbs air rapidly, and I should think that the extensive oil surface exposed to air in the gland oil reservoir would permit a considerable absorption of air by the oil. Much of this reabsorption of air could be prevented by simply floating a board on the oil surface.

I note that no provision is made for automatically interrupting the vacuum in the event of failure of the circulating pump, to prevent flooding the vacuum pump with oil foam, and presume this is done manually. With the system described in my own paper an automatic interrupting device is used, due to the relatively high vacuum maintained in the vacuum tank, which would cause the tank to fill quickly with oil foam following a shutdown of the circulating pump if the vacuum were not interrupted.

The use of a dryer for the hydrogen within the generator casing such as is described in this paper, has not been found necessary with our own hydrogen-cooled generators. This may be partly due to the relatively high degree of vacuum treatment of the shaft sealing oil which is obtained, and also to the fact that a small dryer is provided in connection with the hydrogen-purity indicator. During the first few weeks of operation, however, considerable moisture is present in the casing as a result of the casing having been open to atmosphere, which requires rather frequent renewal of the dryer of the purity indicator. We have provided, with our earlier machines, a dryer for drying the hydrogen admitted to the casing from the hydrogen containers, but this has been found unnecessary due to the high degree of dryness of the hydrogen in the containers, and is being omitted with our later machines.

This paper is a tribute to the extensive engineering work performed by the authors and their associates in connection with the development of the hydrogen-cooled generator, and I congratulate them on the excellent design they have achieved.

F. D. Troxel (Sargent and Lundy, Inc., Chicago, Ill.): A review of the developments and use of hydrogen gas as a medium for the cooling of rotating electrical machines, particularly large high-speed turbine generators, is very timely since several machines have now been in service for several months and considerable operating data and experience are available. Now that the initial steps in the practical use of hydrogen-cooled generators are well under way, there are several facts which are quite evident:

1. That larger and more efficient hydrogen-cooled generators can be successfully built into a given space than air-cooled machines.

2. That the shaft seals which were long the subject of much discussion and many costly experiments, are operating without any serious trouble and with a small amount of gas leakage.

3. That the fear of disastrous explosions is rapidly disappearing.

The authors have prepared an excellent paper and have discussed the design and operating experience of hydrogen-cooled generators, particularly from the viewpoint of the manufacturer. While the operation of hydrogen-cooled generators, has, in general, been considered satisfactory, from the operating company's viewpoint there are certain improvements and developments which should be made in connection with future machines, namely:

A. The hydrogen auxiliaries should be simplified and reduced in number.

B. Means should be developed for taking the hydrogen out of the generator and for refilling in a much shorter time.

C. Standardization of the explosion strength requirements of the shell should be adopted to cover both distortion and failure, and standardization of factory tests to prove the design. Before adopting any standards relative to shell strengths, the question of the real necessity of explosion-proof shells, and their economic justification should be carefully considered.

In connection with the planning and installation of hydrogen-cooled generators, there are certain precautions which should be kept in mind, as follows:

A. All oil tanks and connecting pipes should be carefully vented and grounded. Several small explosions have resulted from lack of attention to these details.

B. There should be no pockets under the generator and around the generator foundation in which gas can collect. If such pockets are unavoidable, some type of ventilating system is required to keep the air slowly moving through these areas.

C. It is desirable for safety reasons to store the hydrogen-supply bottles outside of the building. By locating the hydrogen-supply bottles outside of the building and there connecting them to a header piping system which pipes the gas into the generator, the amount of hydrogen in the building is reduced by about one-half, assuming a normal supply approximately equal to that in the machine. This is desirable from safety and insurance consideration. If the bottles are stored and racked outside of the building on a sheltered platform of suitable height located alongside a driveway, the bottles can be unloaded from a truck or reloaded with very little labor. On the other hand, if the bottles are located under the machine, it is necessary to unload them from a truck, pick them up with the crane, move and lower them to a position near the generator, and then roll them into their rack. The handling of the empty bottles is, of course, similar in the reverse order. All of these steps require time and labor, the cost of which in the course of a year amounts to a considerable sum.

The use of hydrogen cooling introduces one problem in connection with the temperature rise and rating of generators which has not been encountered in air-cooled machines. Since the coolers are located within the machine casing, the distance from the points where the gas leaves the coolers and where it enters the laminations, is very short, and as a result, there appears to be a stratification of the gases in those areas in so far as the gas temperatures are concerned. Several degrees difference in temperatures have been noted on thermocouples a few inches apart. This difference is particularly important since the temperature-detector elements upon which the temperature rise of the generator is determined are located in these areas. This condition does not exist in the air-cooled machines, since the coolers are generally located some distance from the generator, and the cooling medium is thoroughly mixed and has reached a uniform temperature when it enters the generator.

As a result of this condition, it has been suggested that for hydrogen-cooled machines the temperature of the cooling water in going to the air cooler be used as a base, that

the temperature rise be determined from this base, and the rise so determined be used in the guarantees and in the determination of hydrogen-cooled generator ratings in a manner similar to that which has been used for many years in connection with water-cooled transformers. We feel that this suggestion has considerable merit.

C. C. Sterrett: We wish to thank the following gentlemen for their discussions of our paper: S. H. Mortensen, Sterling Beckwith, F. D. Troxel, D. S. Snell, C. F. Hill, and L. J. Berberich.

Mr. Mortensen's comments relative to removing air or gas from the generator housing by evacuation are interesting. We have preferred to use the inert-gas method of removing air or gas from the generator housing because we believe this is simpler and has considerable advantages not provided by the evacuation method.

In hydrogen-cooled turbine generators of our design, three-fourths load may be carried, air or CO_2 cooled. We are, therefore, able to change the gas in the generator housing with three-fourths load, whereas if the evacuation method were used, the generator load would have to be reduced to zero while the generator housing was evacuated.

The possibility of a fire in a hydrogen-cooled machine, or of a failure of the gas control or oil system is rather remote, but if this should occur, it would be desirable to have a positive means of scavenging the generator housing readily. This may be done with a CO_2 scavenging system, whereas the evacuation method would require a vacuum pump or ejector, and it might be that the power for operating this equipment would not be available when required.

We are able to scavenge air or hydrogen from our generator housing with CO_2 in less than 45 minutes, and we doubt that the evacuation method would reduce this time unless a very large vacuum pump or ejector were used.

The only advantage of the evacuation method is that it require slightly less hydrogen for the filling operation. In our gas system, two volumes of hydrogen are required to fill the generator at standstill, whereas with the evacuation method, Mr. Mortensen points out only $1^1/_4$ volumes of hydrogen are required. Since the additional hydrogen required by our method would cost about $15 a filling, we cannot justify the evacuation method. We are able to add the necessary hydrogen to our generators when running (four volumes) in an hour or less and this time is reduced in half when the generator is at standstill.

Mr. Mortensen informs us that he has found seal oil treatment unnecessary in his design. Our experience does not bear this out. Turbine oils, and especially those used in "topping units," contain traces of water. This water will be liberated into the generator housing at the shaft seals and will eventually build up the dew point in the generator. We would suggest Mr. Mortensen measure the dew point of the gas in their hydrogen-cooled machines. We believe he will find a high moisture content in the gas in the generator housing. As pointed out in Messrs. Berberich and Hill's discussion of our paper, low moisture content in the generator housing is very desirable.

Sterling Beckwith's suggestion to simplify the gas and oil systems of hydrogen-cooled machines is timely. In our paper, the statement is made that we have passed through the development era of hydrogen-cooled turbine generators, and we are now turning our attention to simplification of the auxiliary equipment. Hydrogen-cooled turbine generators which are now in operation require no more attention than a corresponding air-cooled machine. We have probably been too conservative in the design of our auxiliary equipment, and are now simplifying our equipment so that it will require much less attention. The operating companies have accepted hydrogen cooling very favorably and have offered many valuable suggestions which will aid in simplification of our auxiliary equipment.

We do not expect to eliminate the relief valve as suggested by Mr. Beckwith. Our later machines are equipped with a very simple relief valve, and we set it to release gas at a pressure above the normal operating pressure range. The relief valve acts to limit the pressure; however, excess pressure resulting from failure of the inlet system would do no harm. We believe it is desirable to keep the gas pressure under control automatically. As pointed out by Mr. Beckwith, the relief valve does not aid in reducing the explosion pressure by releasing gas, since the explosion pressure only lasts a few seconds.

Mr. Beckwith suggests that operation of hydrogen-cooled generators at higher pressures might not be justified due to increased hydrogen consumption. We expect to be able to build gas-tight housings for turbine generators which will not require more than 100 cubic feet of hydrogen per day to maintain 15 pounds in the generator. The cost of this gas will be insignificant with respect to the value of the additional load available at the higher operating pressures.

We enjoyed reading F. D. Troxel's discussion because it represents the operating companies' viewpoint. Mr. Troxel suggests it would be desirable for safety and operating reasons to store the hydrogen bottles outside the building. We do not believe this is necessary from a safety standpoint, but we agree that it might simplify the handling of the hydrogen bottles. So far as we are concerned, the hydrogen and CO_2 supply may be located wherever the customer desires, but we have left this location up to the customer.

Mr. Troxel further suggests that the temperature of the cooling water going to the gas coolers should be used as a base instead of the gas temperature leaving the coolers, for determining the temperature rise used in guarantees. We are in full agreement with Mr. Troxel on this point and we favor a standardization program on this basis.

Relative to Mr. Snell's discussion, we have the following comments. In our earlier generators we provided two gas coolers placed crosswise in the generator housings. Each cooler had a single section and it was necessary to shut down the generator for servicing either or both gas coolers. Operation with these machines has been very satisfactory. However, in our later design we have installed two and three sections in each of the two coolers and a section may be cleaned at a time without reducing the load on the generator. Mr. Snell has suggested that the type of shaft seal used in our design has the disadvantage of having loose parts which may fail, or not be aligned with the shaft. We disagree with Mr. Snell and point out that the floating-ring type seal which we are now using has operated satisfactorily in seven machines for a considerable time on both 1,800- and 3,600-rpm machines. The floating-ring type seal we use is similar to the seals which have been used with success on turbine shafts for a number of years.

Relative to Mr. Snell's comments on the effectiveness of our vacuum-treating unit, we refer to our paper under "Operating Experience." We stated there that our machines were using 20 to 90 cubic feet of hydrogen per day and maintaining hydrogen purity well above 95 per cent. We believe this indicates satisfactory performance of our seal oil system. Mr. Snell has questioned as to how we control excess foaming in the vacuum oil tank. We do this with a "vacuum breaker," which admits a small amount of air and breaks the foam. The vacuum breaker is operated by a float which rides the foam in the vacuum tank. It is our experience that an excess amount of water will overload the vacuum tank and cause foaming. In our design this operating condition is taken care of almost instantly by the vacuum breaker.

We wish to take this opportunity to compliment Mr. Snell on the splendid paper he has presented on hydrogen cooling. He has covered the subject of hydrogen cooling thoroughly, and in our opinion left very little open for discussion.

Electrical Equipment on Machine Tools

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NONMEMBER AIEE

THIS is an interesting opportunity to speak to electrical engineers, to praise them for the excellent motors and controls which have helped us to improve the performances of machine tools, and yet to prod them a bit about a few features of their designs which are obstacles to a greater use of electrical equipment. This paper is thus a partial report to electrical designers describing some of the recent applications of electrical equipment to machine tools and outlining a few of the problems which have been encountered.

Machine tools are rapidly becoming motor-drive machines. Ten years ago we would estimate that about 40 per cent of the machines made by Brown and Sharpe were motor driven. Today over 90 per cent are equipped with motors and many new machines are being designed solely for individual motor drive with no provision for overhead group drive. Not only has there been a shift from group to motor drive, but there has been an increase in the number of motors used on machines. Today milling machines commonly employ three individual motors while grinding machines require from five to seven separate motors.

Now if individual motors are to be used to drive various units of a machine, it is a logical step in design to use more fully the abilities of these motors, to interconnect their controls, and to co-ordinate their functions. Thus instead of engaging and disengaging a clutch to start and stop a mechanism, the driving motor may be started and stopped. Instead of applying a mechanical brake, a motor may be plugged to rest, and in place of a reversing clutch, the motor may be reversed.

Electrically Controlled Milling Machine

The milling machine shown in figures 1 and 2 successfully uses these natural functions of its motors. This is a plain milling machine in which separate shell-type motors drive the spindle and table. The table starts, stops, and reverses with its motor. In stopping the motor is plugged to rest or to the point where it actually makes a few revolutions in the opposite direction. The coast of a few turns in the opposite direction withdraws the work a few thousandths from the cutter, but has no influence on the point of farthest table advance or the point of reversal. By reversing and plugging the motor, it is possible to maintain with great accuracy, the point at which it is desired to stop a cut or to reverse in the cut when cutting to a shoulder. A small motor can stop in less than two revolutions when plugged. With an 1,800-rpm motor, producing a two-inch feed rate, two revolutions represent about 0.002 inch of table movement. Variations in stopping movement due to changes in line voltage might be as much as one-half motor turn which would mean 0.0005 inch at the table. Now of course variations in the operating time of control devices will have an influence on the reversal position yet even with these, the point of table reversal is maintained with surprising accuracy. For example, it is possible to take a very deep heavy cut in which the table is reversed by a table dog while in the cut. The curved surface left by the cutter on the work may be coated with Prussian blue and the table cycle repeated. The cutter will just kiss the blued surface, but will not completely scrape the color from the surface. The cycle may be repeated many times with the cutter always touching the blued surface yet never completely removing the original surface. For such accuracy of reversal, credit is given to the motor and controls for in mechanical designs, we have not obtained this degree of accuracy.

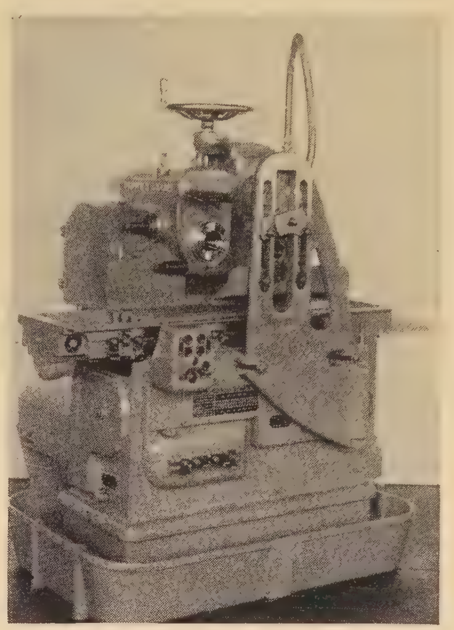

Figure 1. Electrically controlled plain milling machine

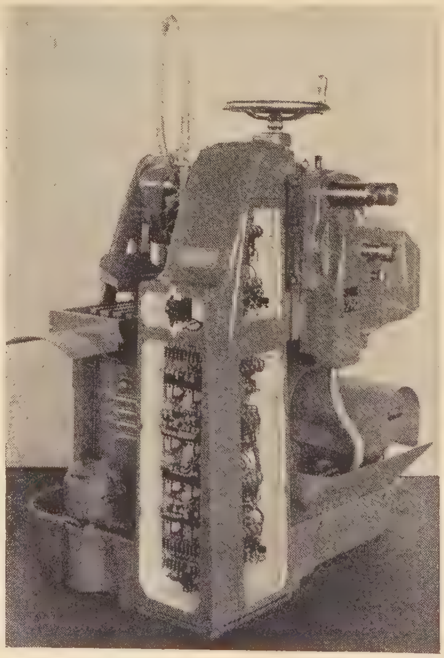

Figure 2. Control compartments on milling machine

A clutch shifted by a solenoid gives feed and fast travel rates of table movement. Using a solenoid to shift the clutch, it becomes comparatively easy to tie in the spindle rotation with the movement of the table. In a normal cycle the cutter spindle will rotate only when the table is moving at a feed rate. A selector switch provides other possibilities where the spindle rotates continuously or rotates only when the table is in motion. This interrelation of spindle and table movements is a feature obtained quite readily in an electrically controlled machine. This same feature is not available in mechanical designs.

When cutting to a shoulder, the table feed is usually stopped by a shift from feed forward to fast travel in reverse. In this move, it is essential that the shift to fast travel be delayed until the motor has been reversed or has at least reached zero speed in its reversal. If quick traverse is engaged before this, the table will jump ahead, jamming the work into the cutter. To obtain the desired sequence of action, a viscosity switch is employed. This is a switch which is controlled by

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the direction of motor rotation. Typical switches are shown in figures 3 and 4. The inner drum is mounted directly on the motor shaft and the outer cylinder is rotated a few degrees by the viscous drag of a 0.002-inch film of oil. The circuit of the clutch solenoid is held open by the viscosity switch and is closed only when the motor has completed its deceleration and is moving in the reverse direction.

Since the viscosity of an oil changes rapidly with temperature, a viscosity switch cannot be expected to act at exactly the same point each time the motor is stopped by plugging. A switch may be expected to open somewhere between a speed of 500 rpm and zero or if a very light restoring spring is used between zero and −500 rpm. Since a few thousandths table drift away from the cutter is not only acceptable, but desirable, the zero to −500 rpm zone has been adopted for the table motor. In stopping, the motor always passes through zero speed and makes a few revolutions in the opposite direction. A solenoid-operated detent prevents the switch drum from being carried through neutral to make contacts on the opposite side as would be done in a complete reversal.

The cutter spindle motor is plugged to rest. Here the switch springs are selected to overcome the viscosity drag when the motor reaches the 500-rpm-to-zero speed range. The plugging is stopped before the motor reaches zero speed, but in plugging, a 3,600-rpm motor to 500 rpm or less 98 per cent of the kinetic energy has been absorbed and a light-duty brake can be used to bring the motor to a complete stop and hold it there. A solenoid releases a spring which applies the mechanical brake as soon as the viscosity switch opens the control circuits.

Making more complete use of electrical equipment, it is possible to adopt a two-speed feed motor. A mercury switch tipped by table dogs selects the high or low table feed. With the possibility of halving feed rates at desired points in the cut changes in depth or width of cut can be more readily handled. Change of feed during a cut is a feature made possible by the use of electric controls. It is a feature which has not been offered in mechanical designs.

One other interesting advantage of an electrically-controlled machine is that the machine can be made inoperative as soon as any door or cover is opened. The doors of the spindle and table gear cases of this milling machine both open motor control circuits and make it impossible to start the machine accidentally while gears are being changed.

Electrically Controlled Grinding Machine

The electrically driven and controlled plain grinding machine shown in figures 5, 6, and 7 is probably the most completely electrified of any standard machine tool now made. It employs seven motors and two d-c generators; the direct current being used for variable-speed drives.

Briefly described, the machine has five constant-speed motors which are connected to the line and may be alternating current or direct current depending on the power supply. These constant speed motors are:

1. *Spindle Motor.* This is the main motor which is mounted on the wheelslide and drives the wheel spindle through a short V-belt drive. The motor runs all the time the machine is in operation.

2. *Coolant-Pump Motor.* This motor is started and stopped to start and stop the flow of coolant.

3. *Lubricating-Pump Motor.* Starting and stopping with the wheelslide motor, this motor-driven pump supplies lubricating oil to the entire machine.

4. *Wheelslide Quick-Return Motor.* (Figure 8) This motor with its solenoid-controlled brake, starts and stops each time the wheelslide is withdrawn from or advanced to the working position.

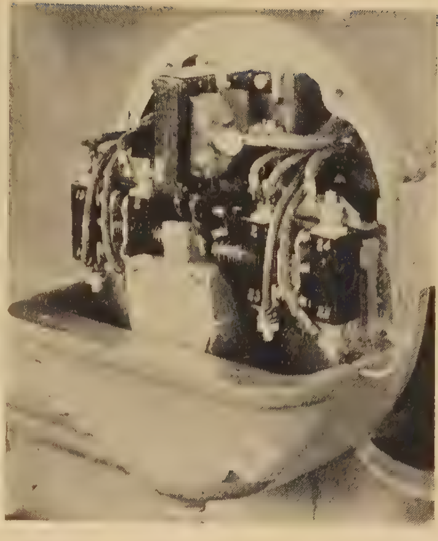

Figure 4. Table-motor viscosity switch

5. *Generator Motor.* (Figure 9) Running whenever the machine is in operation, this motor drives the two d-c generators.

Of the two generators, one is a constant-potential machine, and the other, a variable-voltage generator which is used in a Ward-Leonard table drive. The constant-voltage generator supplies power for relays and contactors, and for the fields of the variable-voltage generator and motor. In addition, it feeds the adjustable-speed motor used to drive the headstock.

The speed of this totally enclosed headstock motor may be varied through a four-to-one range by a rheostat connected in the field circuit. When the motor circuit is opened, a resistance is placed across the armature and rapidly brakes the headstock to rest.

The table motor is controlled by a rheostat in the field of the variable-voltage generator. Reversal of the generator field reverses the table motor. This Ward-Leonard drive was chosen because table loads were essentially constant-torque loads and because a low-speed motor having a small kinetic energy could be readily reversed. Since reversing contactors handle only the small generator field currents, light control units can be used. Speed changes of four to one (900 to 225 rpm) are obtained in the high-gear drive and eight to one (900 to 115 rpm) in the low-gear drive. To obtain an accurate reversal in the high-gear series the motor is slowed down to a low speed just before the reverse contact is tripped.

The outstanding advantage of a completely electric machine is the opportunity given to interconnect the controls of its various units. Controls can be simplified

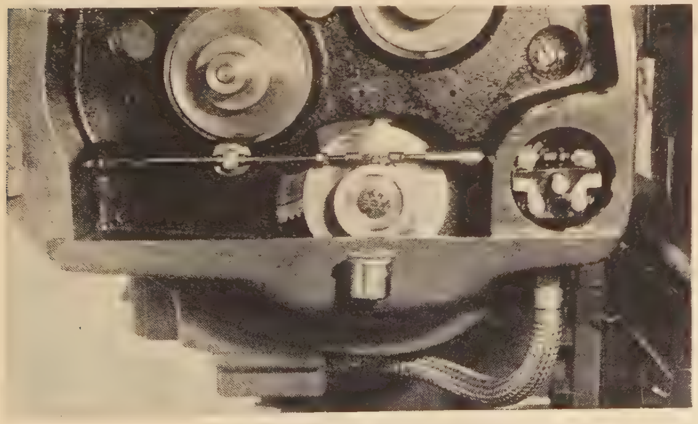

Figure 3. Spindle-motor viscosity switch

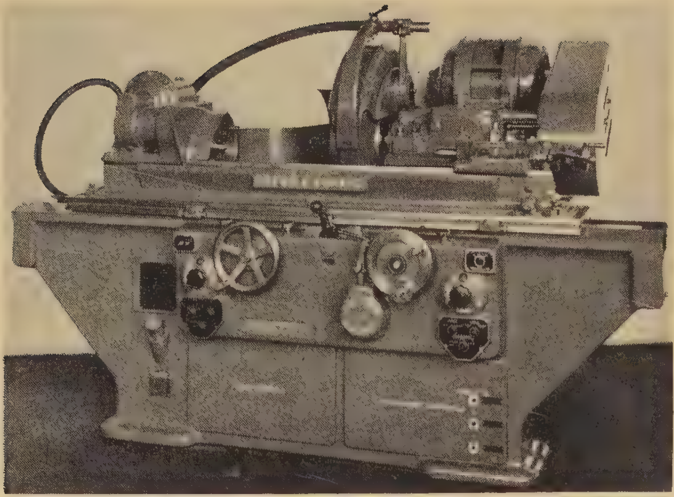

Figure 5. Electrically controlled plain grinding machine

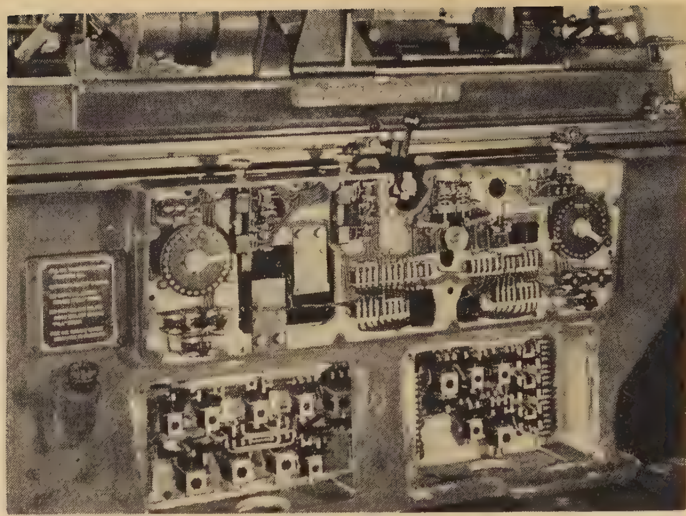

Figure 6. Machine of figure 5 with front plates removed

and co-ordinated, safety features can be easily incorporated, automatic control becomes possible, and in general the machine becomes more responsive to the operator. No other method of control can so easily tie together the various elements of a machine. This is the function of electric control which should receive greater emphasis and it is here that the electrical engineers can do some helpful work in the machine-tool industry. Machine tools are now using a large number of electric motors but the possibilities in controls are still to be developed.

Now taking the basic driving elements of the grinding machine just described, let me discuss a few of the possibilities in control. The piece to be ground having been placed in position, the operator must start the headstock, must turn on the flow of coolant, must start the table, and must bring in the cross slide to the grinding position. Four separate units must be controlled. If all of these are electrically powered as in the machine described, they can be simultaneously started by the rotation of the cross-slide handwheel. Four operations are thus easily replaced by one. When the piece is ground to size there are five steps to be taken: the wheelslide must be withdrawn, the table must be stopped, coolant must be shut off, power to the headstock must be disconnected, and a brake applied to quickly stop the work. By interconnecting controls all of these functions can be executed by a partial turn of the cross-slide handwheel.

An operator is traverse grinding with a table dwell at each end of the table travel and has controls centered in the handwheel. The grinding wheel must be trued. To do this the following moves must be made.

(*a*). Table dwell should be eliminated.

(*b*). A slow rate of table movement must be selected.

(*c*). As a safety measure the wheelslide quick return should be made inoperative.

(*d*). Normally the coolant pump and headstock start together. Here it is desired to start the flow of coolant, but to keep the headstock at rest.

(*e*). The controls centered in the handwheel should be separated so that the table and coolant flow can be started together by a control knob.

All these operations can, in an electric machine, be made simply by turning a selector switch or by changing the position of a knob from "grind" to "true." Having dressed the wheel, all original settings can be restored by turning the switch back to the "grind" position. No time is lost in resetting speeds and feeds, and there is no uncertainty on whether or not all the necessary moves have been made.

With electric control for all units of a machine, it is comparatively easy to break into the control circuits for the purpose of tying in special attachments or devices which are to take part in the operation of the machine. For some production jobs, automatic sizing or gauging devices are placed on the work. Such gauges can be wired to make or break a control circuit and thus to withdraw the wheelslide and stop the table, headstock, and coolant pump, leaving the machine ready for removal of the work.

In much the same way, an oil-operated piston can be placed in the lubricating system and can be wired to stop the entire machine whenever oil pressure becomes abnormally high or low.

The two machines described suggest some of the possibilities in machine-tool design which are offered by electric motors and controls. Through the wise use of electrical equipment machines can be given new abilities or features and can be made to perform standard functions with greater ease and increased accuracy. Of special importance are the gains which can be made through the use of electric controls. Most new machines will be motor driven and it is thus suggested that design development be focused on using to the fullest extent, the abilities of motors and on co-ordinating and simplifying their controls.

Controls

In starting out on the design of electrically controlled machine tools we realized that there were several characteristics of machine-tool service which were different from the service for which many control units had been designed. Life tests were thus made on a number of different makes and types of relays and contactors, to determine those which were best suited for our requirements. In these long tests, it was found that many standard relays and contactors performed poorly or failed completely in machine-tool service. Since electrical engineers are considering altering their designs to meet some of these new service conditions, it may be helpful to discuss these in detail.

Frequency of Operation

Electrical control equipment for machine tools should be designed to have a life of at least 10,000,000 cycles or operations. In the machine-tool industry, it is expected that machines will serve reliably for many years and any machine which requires frequent replacement of

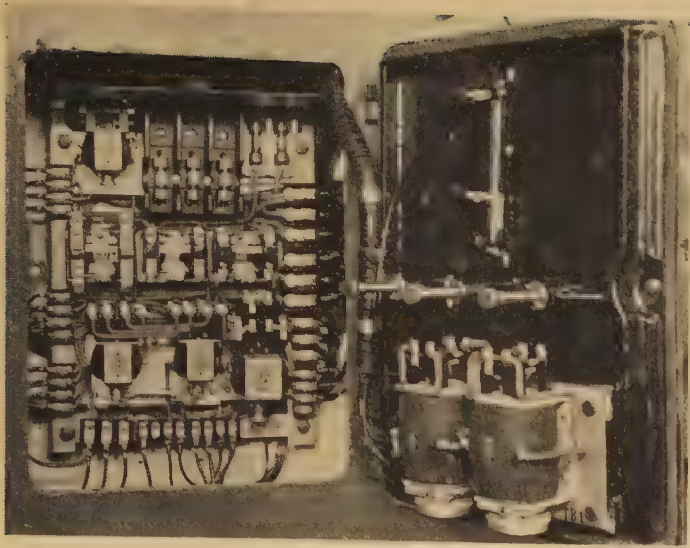

Figure 7. Side compartment for wheelslide controls

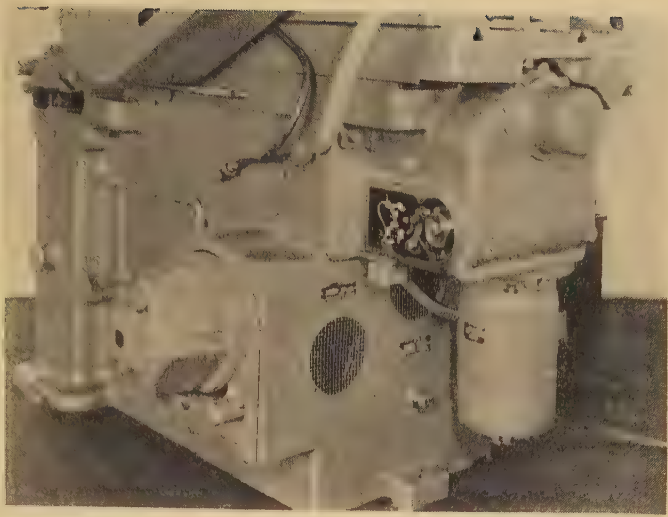

Figure 8. Wheelslide quick-return motor and cam control

parts is handicapped in its appeal to the trade. On production or manufacturing machines, control devices are operated almost continuously. Ten-second work cycles are common and in a complete cycle relays and contactors may be operated two or more times. With controls being energized every five seconds, it does not take many months to get into the million zone of operations. This is a far different service from that where controls are mounted on the walls of a room and operated a few times a day.

From the life tests we have conducted, it has been found that many standard controls have operating lives far under the 10,000,000 standard which we have tentatively adopted. With this number of operations, fatigue and wear failures were common. Pins and washers wore out, screws became loosened and springs, guides, and contact arms broke. Especially common were the failures of shading coils which wore or broke and caused noisy operation. In several cases these coils had failed in a few hundred thousand operations. Life tests frequently ended with the failure of the relay coils. The small wires with which the coils are wound, broke off at or just before the points at which they were joined to the coil terminals. The terminals were not well supported or anchored in the coil jacket or tape covering and the small movements and vibrations of the terminals caused a fatigue failure of the leads. It would appear that greater attention to the mechanical design of controls would improve their useful lives and would better qualify them for use in machine tools.

Certainty of Operation

Most machine tools of the manufacturing type have a fast travel movement which brings the work into cutting position. The point at which the shift from the fast travel to the feed rate occurs must be consistent, for operators set dogs for the shortest possible feed movement and variations in shifting position may cause the work to hit the cutter while still moving at the fast travel rate. As an example, the table of a machine moving at 300 inches per minutes is allowed a variation in shifting position of 1/16 inch due to variations in time of operation of electrical devices. This 1/16-inch represents but 1/80th of a second. If electrical equipment does not operate consistently within this variation limit, there will be occasional crack-ups in which cutters are injured or the work destroyed.

From life tests, it has been found that very few devices will consistently operate within the 1/80-second limit suggested. Designs which have several rubbing surfaces seem to be the least qualified to function with accuracy. Pin friction and losses in links and arms are variable and changes in friction conditions easily cause delays in operation, especially in the time of dropping out after being deenergized. Direct-acting units with simple movements have in our tests had the greatest consistency of operation.

After repeated operations, we were surprised to observe that relays and contactors would occasionally stick and fail to drop out or would be very sluggish in their dropping out. Examination revealed that the surfaces where the armature pressed against the pole faces were sticky. It was at first assumed that the black gummy coating was caused by dirt which had entered the control compartments. To check this, devices were operated in a sealed box. The same coating still appeared to cause sticking. Next, it was assumed that the varnished coils were contributing the gum and so unvarnished coils were tried with no success. It became apparent then that the laminated steel members of units were themselves contributing the gum. The varnish or resinous coating used as an insulating material on the iron sheets was very slowly working itself on to the seating surfaces. Baking the sheets had not prevented the coating from being hammered into a plastic gum.

On checking with other manufacturers, we learned that this trouble with sticking relays and contactors is common. Since the experience of having a relay stick is to a machine operator much the same as

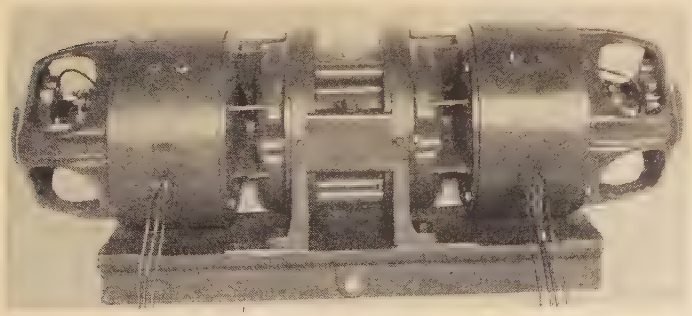

Figure 9. Motor generator set

that of a driver who steps on a brake to find it useless, it is suggested that electrical designers study the problem in their new designs.

By using intermittent-rated coils where the application permits it, it is possible to get greater pulls and thus use greater opening-spring pressures. These will make sticking failures less common, but the move is only a partial solution to the problem. Another partial solution is the use of two units in series. The probability of both devices sticking at the same time is of course far less than that of a single unit sticking. The best solution we have found is the use of opposed relays. As one is de-energized, the other is energized and assuming the first sticks, the second after moving one-fourth inch, gives the first a blow which is vigorous enough to separate sticking surfaces. Should the second coil fail, the first acts just as it would if the second were eliminated. The unit just described has the greatest certainty of operation of any device tested, thus far. The primary objection to this design is its cost.

Ease of Change for 50–60 Cycle

When machines are manufactured in lots of 25 to 100, it is necessary to insert motors and controls in order to run off and inspect machines before going into stock. Since many machine tools go abroad, it is frequently necessary to change these stock machines from 60 to 50 cycle. Motors are made for both 50/60-cycle service but controls are not so rated and must be changed over. It would be a great help to machine-tool builders if relays and contactors could be made for 50/60-cycle service. From tests we have made, it appears that present 60-cycle coils are fully qualified for 50-cycle service and it is difficult to see why manufacturers are so reluctant to give their coils a 50/60-cycle rating. If coils cannot be made 50/60 cycle then designers must simplify their devices so that one coil can be substituted for another in a few simple steps. We have had cases where it has been necessary to eliminate some makes of controls just because the devices had to be practically disassembled to substitute a 50-cycle coil for 60 cycle. In the same way inaccessible over-load heaters make change-overs costly.

Space Requirements

When a control unit is mounted on the wall of a room, a few extra inches in its space requirements are unimportant; however, when the same unit must be mounted in a machine casting, these marginal inches are of critical importance. They may limit the possible power movements of, or may upset the proportions of the machine. In general, the mechanisms in machine tools have been laid out with economy of space as a controlling factor in design. Gears, shafts, clutches, and cams, are assembled in compact units, for steam-shovel proportions cannot be accepted in a sensitive tool-room machine. On such a machine it is a difficult problem to mount electrical equipment and more compact units would greatly aid machine designers. At present, we use few limit switches and push-button stations in their original casings or housings, for these require too much space and have an awkward appearance when attached to the outer walls of a machine. Greater compactness and more economy in use of space would make electrical devices more readily adaptable for machine-tool applications.

Machine Wiring

In wiring a machine tool, it is well to assume that sooner or later, wires will be exposed to oil even though detail design steps have been made to keep them apart. In assembly or repair work, oil is often unintentionally admitted to wire ducts or terminal boxes, and when admitted, it is not likely to be removed. We have thus found it an economical practice to use the high-quality wires insulated with synthetic compounds which make them oil resistant. Wherever possible, ducts of ample size are cast in the machine bed so that wires may be well protected from physical contact with moving parts. It is also very helpful to use prepared harnesses in wiring, for, with wires cut to length, equipped with identifying tags and terminals, and bound together, individual wires do not have to be drawn through the machine and wiring becomes an easier job.

Although oil-resistant wire is available there is no oil-resisting tape to be used on these wires. Taped joints are equally as important as circuit wires and defense against oil will only be half complete until an oilproof tape is developed.

The problem presented by taped joints is aggravated by the terminal boxes on fractional-horsepower motors. Imagine totally enclosed motors being made with terminal boxes which resemble strawberry boxes with their open seams and corners. The fact that an enclosed motor is specified, indicates that surrounding conditions will not be favorable and it is inconsistent to furnish a partially open terminal box on such a motor. A terminal box full of pasty rubber and slimy tape is a hazard in any motor application. Fortunately integral-horsepower motors have well-designed terminal boxes. It would be helpful to bring those on fractional-horsepower motors up to the same standard.

Conclusions

Two conclusions are suggested by this paper. First: that through the use of motor drives and electric controls, machine tools can be improved in performance and can be made simpler and easier to operate. Second: that many standard control devices are poorly qualified for machine-tool service and should be redesigned for this more frequent and exacting duty.

Discussion

P. H. Wilmarth (nonmember; The Blanchard Machine Company, Cambridge, Mass.): Your paper on "Electrical Equipment on Machine Tools" was studied by several of my associates and we all have agreed that the build-up for your final conclusions carry many excellent statements of "constructive inference."

Your illustrations show the last word in good practice in applying both motors and control. The "Frequency" and "Certainty" sections are the meat of the whole situation because the final decision as to whether or not a mechanism should be used in preference to an electrical unit is finally rooted in the fact that ruggedness comes before low cost.

We have recently adopted a design to overcome the 50/60-cycle difficulties you mentioned. This merely consists of a 0.25-kva transformer with a dual-voltage primary (220/440) connected to one phase of the line and a dual-voltage secondary (110/95) for the entire control circuit so that the identical holding coils may be used on either frequency. Further merit comes from the safety feature of the low-voltage control circuit plus a flexibility of application on line voltages which will allow this one panel to be used on about 85 per cent of the machines for which it is designed. The taps allow for a simple change, even after the machine is stocked, because they are brought out to a small terminal block and the whole thing only adds about $10 to the cost of the entire machine tool—a small premium for its manifold benefits. Twenty-five-cycle or 550-volt currents account for nearly another ten per cent but still have the transformer, with fixed ratio windings.

B. N. Foster (nonmember; Kingsbury Machine Tool Corporation, Keene, N. H.): We have read this paper over and agree with practically everything you say. Some of the points which you bring up are not of much interest to us personally and there are some points which you do not bring up which are of vital interest to us, but from our small knowledge of the subject you have covered the milling and grinding machine

situation very thoroughly and accurately.

I am a little bit sorry not to be able to offer some sort of constructive criticism here for I realize that your request for criticism was seriously made and that other viewpoints might be of use to you in your work with the committee. However, I can't think of anything offhand to talk about unless I get into a long discussion of some points not brought up in your paper which have no direct relation to the particular corner of machine tools which you are covering, and I don't know whether you would want this information at this time, and furthermore I don't know how we would have time to do this.

You realize, of course, that I am very much interested in the work which is being done by your committee in an effort to straighten out this entire electrical snarl and will be very glad to do anything I can to help. At present, however, the business conditions here do not permit me to spend very much time on matters of this sort. However, if specific points come up on which you would like to have me express an opinion, I would be only too happy to do so and would like to have you feel free to write me at any time on these matters and hope that I will be able to answer you satisfactorily.

G. H. Garcelon (Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): I think you will find that manufacturers of industrial control keenly appreciate the problems encountered in machine-tool applications and are giving them considerable thought in their development programs. One characteristic difficulty is that several of the features required tend to increase the cost and size of the equipment which is, of course, directly opposed to the general desires of the machine-tool industry. You have cited items in your paper directly illustrating this point, as for example under the section titled "Certainty of Operation." There are several ways to secure greater accuracy in the time of operation and to decrease the possibility of failure to operate, but unfortunately all of them increase cost, size, or both.

In regard to the ease of changing the coils from 50 to 60 cycles you state that tests indicate that 60-cycle coils are fully qualified for 50-cycle operation. Normal 60-cycle coils and magnets are designed for an operating range of 85 to 110 per cent of rated voltage which is considered necessary to insure satisfactory operation. If these coils and magnets were designed to cover 50 cycles, as well as 60 cycles, it would be the equivalent of applying approximately 20 per cent greater operating range and this would necessarily mean larger and more expensive magnets and coils.

Some tests may indicate that commercial designs seem adequate for this range, but I am afraid that certain conditions have been overlooked. The operation may be satisfactory in the open or in a large enclosure, but the manufacturer must design these units so that they may also be operated in small enclosures which may represent an increase in effective temperature of the air surrounding the coil amounting to 20 to 30 degrees centigrade. The tendency of manufacturers is to design for a more conservative maximum temperature of coils than is permitted by the standards in an attempt to avoid coil failures after several years' operation under somewhat adverse conditions.

The percentage of 50-cycle applications is small and the coils are rather inexpensive, therefore the best solution of this problem would seem to be along the lines of making the designs such that coil changes can be made readily.

F. H. Penney (nonmember; General Electric Company): I am sure the manufacturers of electrical equipment are deeply indebted to Mr. Graves for his paper. It is at once evident that a great deal of painstaking thought has been given to the selection of the proper control units.

I would like to comment on the reference to the difficulties encountered because of the various voltages and frequencies found not only in the United States but abroad. Unfortunately it has not proved practical to permit the operation of magnetic switches through voltage or frequency ranges wide enough to warrant a dual voltage or frequency rating unless voltage and frequency vary in the same ratio and even then only to a limited extent. Size limitations and the normal voltage fluctuations encountered on standard power systems require about all the margin in design which can be built in and maintain the highly desirable features now provided without adding a range on top of this.

However, a scheme used on certain large panels and to some extent on smaller units offers one way toward the goal of a standardized panel for machines through the 50/60-cycle range with a voltage range from 200 to 550 volts. The inclusion of 50 cycles is particularly important because of the foreign business now coming to machine-tool builders.

The plan briefly is to segregate the control circuit entirely from the motor or power circuit by means of a transformer, selecting some standard control-circuit voltage such as 220 volts, 60 cycles. The transformer, it is true, adds something to the cost. However, the advantage is likely to be considerable where machines are produced in lots of 25 or more since all magnetic switches can be equipped with 60-cycle 220-volt operating coils. Only the overload relay heaters need await assembly when the order comes in specifying voltage and frequency.

The transformer primary equipped with taps can provide for the voltage range 208, 220, 440, 550, 60 cycles; the secondary voltage will remain 60 cycles 220 volts. Likewise if 50-cycle systems are to be provided for, taps are available primary and secondary whereby the correct voltage for 50-cycle operation can be secured. A small terminal board primary and secondary will make possible the correct connections of numbered terminals with very little time or trouble.

The transformer size need only be great enough to care for the maximum number of switches which will be energized at any given time. The cost is more than likely offset by the reduced spares and the reduction in delays occasioned by special coils, etc.

Mr. Graves also refers to the question of a suitable tape for use with Flamenol. This problem seems well along toward a solution and samples of a tape which will conform to the characteristics of Flamenol are being tried where oil and other compounds have made such a product a necessity. The preliminary reports indicate that very shortly a general distribution of the new product can be made.

R. S. Elberty (Landis Tool Company, Waynesboro, Pa.): Mr. Graves' paper is indeed a timely one. There is a growing field for electrical engineers in the machine-tool industry. The electric milling machine and electric grinder are excellent examples of the results obtained in applying good electrical engineering to machine tools. This subject has not received the attention it merits from electrical engineers in general or from the AIEE. Instead, we find such electrical subjects discussed by the ASTE, ASME, or the Machine Tool Electrification Forums held by Westinghouse.

Electrical drives must compete with mechanical or hydraulic devices that are well known to the average designer of machine tools. A. E. Rylander of the Midland Steel Company discusses "The Trend to Hydraulics" in the *Tool Engineer* for April 1939. The 1935 Machine Tool Show disclosed many advances in electric drives, but hydraulic drives had also developed rapidly. In 1939 we shall probably see more evidence of the very keen competition between hydraulic and electric drives.

The electric drive offers many advantages to the machine-tool designer. We have our troubles, as Mr. Graves outlines, but the electrical manufacturers have always been very helpful in developing and applying equipment to meet our needs. Our problems are specific and individual depending on the type of machine tool to which the drive is applied.

Many of my friends have suggested the formation of a society of machine-tool electrical engineers. I do not favor such a move. We can get together on electrical problems through some one of the existing engineering organizations. Perhaps this paper of Mr. Graves will bring about an aroused interest in machine-tool electrification among electrical engineers in general. Certainly there is room right in the AIEE for more papers of this nature.

B. P. Graves: In reply to P. H. Wilmarth's discussion on the paper entitled "Electrical Equipment on Machine Tools" I would like to say that we have done this in the past, although our control voltage is usually twice as high, namely, 220 volts on 60 cycles, and 187 on 50 cycles.

The objection raised is that it makes it more difficult for foreign users to obtain coils, that is, they can sometimes obtain 220-volt 50-cycle coils, but not 220-volt 60-cycle coils.

Because of this difficulty in obtaining 220-volt 60-cycle, we have refrained from using the transformer.

In reply to G. H. Garcelon, I would like to state that the reason that this subject of 50/60 coil was put into the paper, was to bring out the various difficulties and possibilities along this line. If this feature could be accomplished, it would be a material saving in our estimation, to machine-tool builders, and of course we in the ma-

chine-tool industry will have to be governed by the various opinions of the manufacturers of controls.

Our reason for suggesting this thought was the fact that we have been so successful in the use of 50/60-cycle motors.

In reply to the discussion as entered by F. H. Penney of the General Electric Company—there are several points in Mr. Penney's discussion which are of considerable interest, on some of which I feel I would like to express my opinion.

In reference to the difficulty encountered because of the various voltages and frequencies found not only in the United States, but abroad, I rather take exception to Mr. Penney's remarks when he says it has not proved practical to permit operation of magnetic switches through voltage or frequency ranges wide enough to warrant a dual voltage or frequency rating. This has been an argument for sometime among the electrical manufacturers, but now we find one company which has agreed to our plea and in starting this dual-voltage arrangement, several other companies are now following, and this is proving to the machine-tool industry a big saving, both in time and patience. I feel that with a little further study, all control manufacturers will follow along this line.

In reference to adding a transformer, I feel that the general idea is good, and some day we may feel obliged to follow this practice, but it does increase the difficulty of foreign purchasers obtaining a correct supply of 60-cycle 220-volt operating coils. This is one of the points that has been brought up to our attention on many occasions by foreign purchasers.

In reference to suitable tape for use with Flamenol, I am pleased to state that since the meeting we have received two large sample rolls and at the present writing this tape looks exceedingly good to us and may be the means of solving one of our very annoying problems.

In reply to Mr. Elberty's discussion on the paper, there is very little that I can say other than to agree thoroughly with the points that he has brought out.

In reference to the point of machine-tool builders having to compete with mechanical and hydraulic devices, I think this is a point well taken as in my opinion, the electrical companies don't seem to realize that this is a matter that must be most thoroughly investigated by the average designer of machine tools, because it is very imperative in bringing out a new design that it should be in very close alignment with competitive machines, both for price and features.

Regarding the point of designing electric drives and the electrical manufacturers having been very helpful in developing and applying equipment to meet our needs, because of the fact that our problems are specific and individual, depending on its type. This is one of the reasons why it is becoming much more difficult for electrical companies to do the engineering for the machine-tool manufacturers, but I do feel that it should be possible for us to get together with electrical manufacturers, more especially now that we machine-tool builders are inclined to consider the electrical end as part of our daily work, and in tying our two organizations together, to bring about much more interest in the electrification of machine tools.

Modern Trends of Low-Voltage Air Circuit Breakers

J. W. SEAMAN
ASSOCIATE AIEE

Synopsis: The history of low-voltage air circuit breakers has paralleled the development of power distribution. The desire for improved contacts led from an automatic knife-switch type of circuit breaker to an air circuit breaker equipped with a laminated copper brush. The trend from d-c systems to polyphase a-c systems led from the "nontrip free" type of air circuit breaker to the "trip free" breaker; and now the requirements for low maintenance, safety of operation, increased continuity of service, together with the trend to steel enclosing of switchboards and individual devices, is being met by new air circuit breakers equipped with solid silver main contacts, alloy arcing tips, and a new type of arc interrupter herein described.

THERE has been a considerable change in air-circuit-breaker construction during the past several years, due principally to the increased requirements for low maintenance, safety of operation, and increased interrupting ability. In order to emphasize the recent improvements, a review is made of the history of air-circuit-breaker construction.

The first device, which may be classed as an air circuit breaker, was little more than an automatic knife switch. This device probably originated about 1885. Figure 1 illustrates a typical breaker of this construction. Two fundamental requirements, which we have to this day, were met by this device, that is, an operable contact member to open and close an electrical circuit, and an overcurrent trip responsive to abnormal circuit conditions. The movable contact blade was held in the closed position by a mechanical latch that could be released by the overcurrent trip thus causing the opening of the blade and consequent interrupting of the circuit. Secondary contacts of carbon and copper were utilized with this type of device to take the burning on opening and closing of the circuit.

The next major step occurred about 1892 and dealt with the current-carrying ability of air circuit breakers. At this time we find the knife-blade type of contact being superseded by a laminated-brush contact. Improved secondary contacts were also provided for protecting the main current-carrying contacts during opening and closing of the circuit. Figure 2 shows a typical device of this period. This construction was a distinct improvement for carrying current continuously, largely due to the wiping action of the several laminations employed in the main contacts.

Also during this period the first air circuit breakers utilizing a magnetic-blowout chute were produced in answer to the demand for a satisfactory breaker for the many d-c railway projects then active. Figure 3 shows a typical breaker of this period equipped with such a chute.

The three-phase a-c system appeared during this time. A-c motors and other connected devices were then quite small and easily controlled, so that it was not

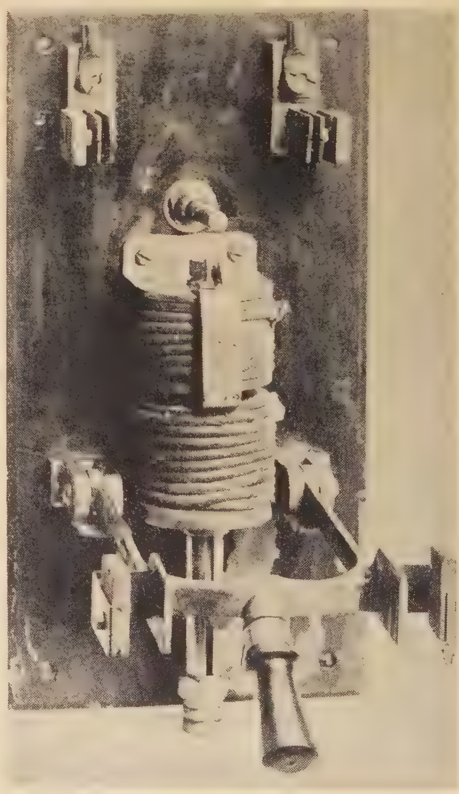

Figure 1. Knife-switch type of air circuit breaker

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until 1905 that the increase in the size of such systems required suitable a-c air circuit breakers. The development of three-phase breakers brought the first real regard for safety of operation. Prior to this period, air circuit breakers for d-c service had been what was popularly called "nontrip free," that is, the operating handle was definitely tied mechanically to the movement of the breaker contacts, and as a result it was possible for operators to hold such breakers in against a severe overload merely by holding the handle in the closed position. As can be readily appreciated, the closing of a breaker of this type against a severe overload or short circuit could readily result in disastrous consequences. The generally accepted procedure for coping with this situation was to utilize a switch in series with the circuit breaker, which could be closed after the circuit breaker had been latched in, thereby permitting immediate opening of the air circuit breaker if the switch was closed against abnormal circuit conditions. To eliminate the necessity for such switches, the so-called "trip free" breaker was generally adopted. With an air circuit breaker of this type, closing against abnormal circuit conditions results in the operating handle being disengaged mechanically from the movable contact structure, rendering impossible the holding in of the breaker under abnormal circuit conditions. Breakers of this type were first brought out around 1905, and as illustrated in figure 4, formed the basic model for all air circuit breakers manufactured during this period up to approximately 1930. The similarity in construction can be readily appreciated by comparing the air circuit breaker shown in figure 4 with the one illustrated in figure 5.

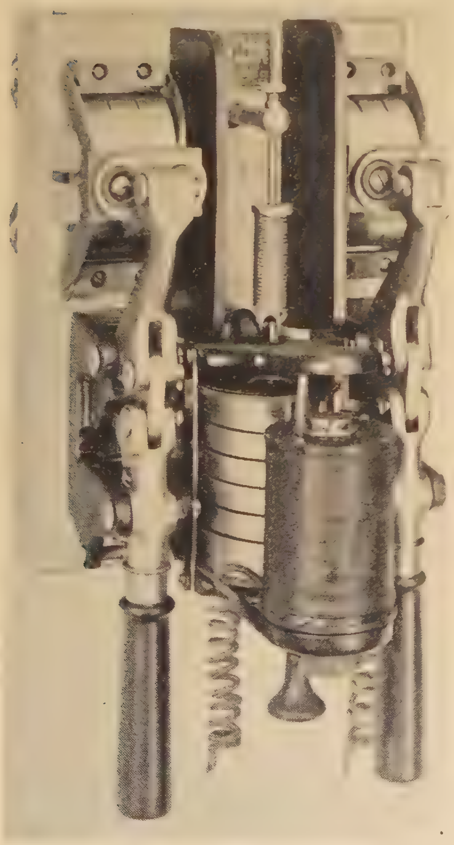


Figure 2. Early breaker with laminated brush

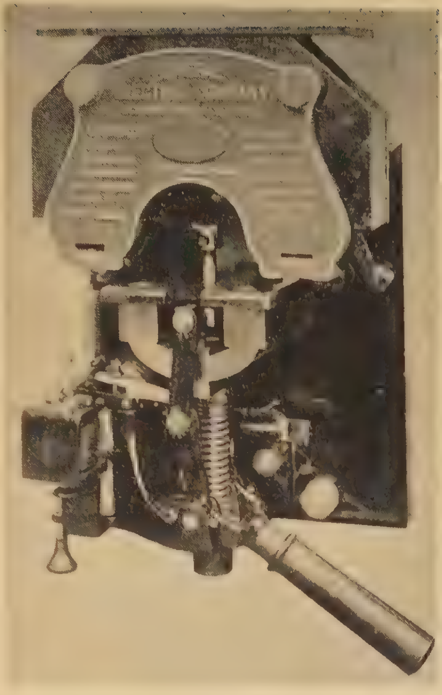


Figure 3. Early magnetic-blowout air circuit breaker

This résumé, while very brief, covers the general improvements up to date. The major contributions to the art appear to be the development of the laminated-copper-brush contact and the trip-free type of mechanism. The use of carbon-tipped arcing contacts which separated in air provided the means for arc extinction. Figure 5 illustrates the type of air circuit breaker in general use in 1930 and in some instances, with minor modifications, still available commercially.

Modern Air Circuit Breakers

In the light of what has transpired in the years prior to 1930, the trend of the past eight years is worthy of note. During this period satisfactory answers to the demand for low maintenance, increased continuity of service, greater safety, and improved current-interrupting performance have become increasingly important. A considerable premuim has also been placed upon such physical factors as space requirements and weight. The

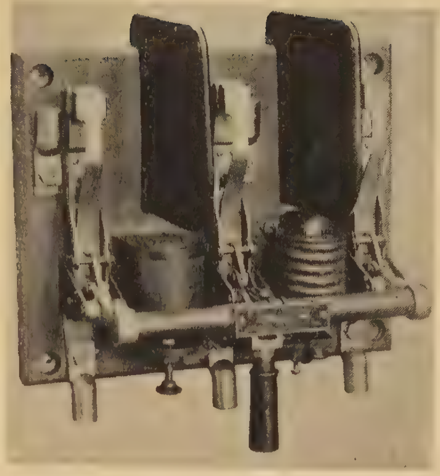


Figure 4. Early trip-free air circuit breaker

work done during the past several years has, we believe, satisfactorily answered and met most of these modern requirements.

Contacts

The first requirement to meet, and the most important at the time, was developing main current-carrying contacts which would require relatively little maintenance and insure the greatest continuity of service. The main contacts utilized prior to this period were of the laminated-brush construction, each lamination consisting of a piece of spring copper. While these contacts were generally satisfactory, it is necessary to acknowledge that copper, in itself, has undesirable oxidation characteristics. If through poor maintenance copper oxide is allowed to form on the contacts, cumulative heating is carried to the point where the spring copper laminations are annealed and the service impaired or interrupted.

Also, the increasing development of industrial processes which involved intermittent circuit overloads as a normal part of the processing cycle made it desirable to develop a contact which would withstand overheating that might cause the laminated-brush type of contact to fail.

After many laboratory tests on numerous materials, pure fine silver was selected as the contact material which would satisfactorily solve these problems. Silver stood out among the materials tested, primarily because of its low contact resistance and stability. Relatively little oxidation occurs on silver. This oxide breaks down at comparatively low temperatures and pressures. Copper oxide on the other hand is mechanically tough and requires rather high temperatures to break it down.

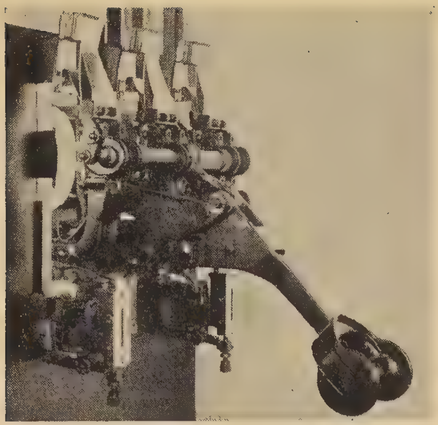


Figure 5. Trip-free type of air circuit breaker, manufactured in 1930

Figure 6 shows a typical contact construction employing fine silver blocks for the main contact surfaces. Contact pressure is obtained by a separate compression spring not in the current circuit. As may be appreciated, a contact of this type may be subjected to severe overload conditions without impairing its current-carrying ability. As may be noted the silver blocks on the movable contact have a convex surface to obtain a line contact. This utilizes efficiently the pressure of the contact spring and assists in breaking down the silver oxide that may form. Figure 7 furnishes a comparison of the physical size of a laminated copper brush and a silver-faced contact of the same current rating. The considerable reduction in size, obtained by the use of silver, has contributed materially to the building of more compact breakers as well as reducing the interrupting time due to the lowering of the inertia of the movable-contact structure. About eight years of field experience with this type of contact has been obtained with very satisfactory results. Following this favorable experience, all of our modern air circuit breakers have been equipped with this type of contact.

Similar work has also been done on improving the arcing contact structure associated with the main current-carrying contacts. The use of alloys which have a much lower resistance than the carbon materials formerly employed and also greater mechanical strength provides the greatest improvement in this particular phase of construction. These alloys permit much better current transfer from the main contacts during arc interruption than was formerly enjoyed.

Interrupting Units

The next problem dealt with the necessity for handling large blocks of power, due to the substantial increase in the short-circuit capacity of a-c systems. Until recently, no particular attention had been paid to the interrupting capacity of air circuit breakers as the connected capacity was generally small. A listing of interrupting ratings for low-voltage air circuit breakers was published on May 26, 1938, by the large-air-circuit-breaker group of the National Electrical Manufacturers Association under section *SG*-7-26 and is the first generally recognized list of air-circuit-breaker interrupting ratings. It had been generally considered that in low-voltage a-c systems it would be impossible to get short circuits of much more than 20,000 amperes. However, in recent years increased system capacity and larger industrial processes have resulted in the possibility of obtaining short-circuit currents of the order of 60,000 to 80,000 amperes, and in some instances even higher. Thus the necessity of air circuit breakers with adequate and proved interrupting ratings. This, coupled with the fact that in the interest of safety and low cost of installation, there has been a considerable trend toward factory-built steel-enclosed switchboards and steel-enclosed individual breakers, necessitated a considerable study for adequate and safe means of controlling high-power arcs.

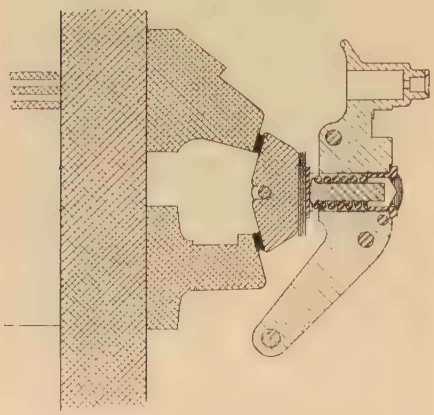


Figure 6. Typical silver-contact arrangement

While prior to 1930 considerable work had been done on arcs in oil, relatively little had been done concerning the study of high-capacity arcs in air. It is granted, of course, that the addition of arcing contacts to air circuit breakers, as shown in figure 5, would considerably increase the current-interrupting ability of air circuit breakers, particularly if considerable head room above the arcing contacts is provided. In addition to this, the magnetic-blowout chute, as shown in figure 8, is adapted to interrupting large amounts of currents if no difficulty in the nature of adequate air space over the top of the chute is encountered. As a matter of fact, the device, as shown in figure 8, equipped with magnetic-blowout chute has satisfactorily interrupted currents of the order of 330,000 amperes root-mean-square in a remarkably short time, as is illustrated in figure 9. Such a test demonstrates very clearly the rapidity with which currents of such magnitude can be completely extinguished. It is not feasible, however, to apply such breakers in the limited compartments associated with steel-enclosed air circuit breakers, the reason being that inadequate head room will greatly impair the interrupting ability of such a device. The satisfactory handling of currents of large magnitude in small steel compartments, therefore, greatly complicated the problem of developing a suitable arc interrupter which would be applicable over a wide range of interrupting ratings. After investigating several different ways of attacking this problem, the "pin-type arc quencher" was decided upon as the type of interrupter most generally applicable to a wide range of interrupting ratings. This device has now been successfully applied to air circuit breakers whose interrupting ratings range from 10,000 amperes to 80,000 amperes, at 600 volts alternating current.

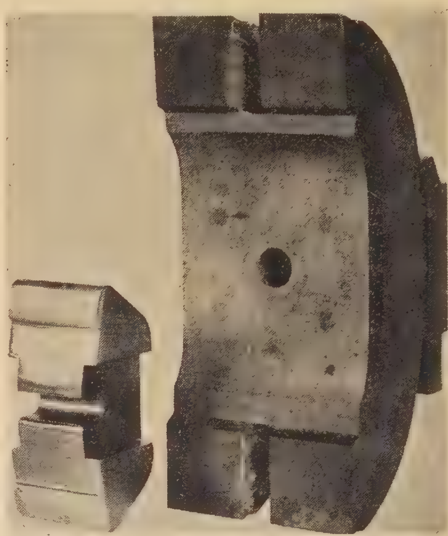


Figure 7. Size comparison of solid-silver contact and laminated-copper-brush contact

A typical arc chute of the pin type is shown in figure 10. A pair of soft-iron U-shaped magnets is attached to the alloy arcing contacts to drive the arc rapidly into the pins located above. The pins are positioned with respect to each other so as to develop the maximum volt-

age gradient. As the arc is driven into the pins it is broken into a series of arcs which travel through the pins until extinction is complete. Located above the pins is a series of baffles spaced apart so as to provide a series of narrow slots through which the gases generated by the arc escape. The width of each slot is proportioned so that the arc itself is confined within the chute. This, coupled with the cooling of the arc gases in traveling through the slots, eliminates the possibility of the arc striking to nearby grounded metal parts. The extinction of the arc is due primarily to two reasons—first, to the voltage gradient obtained from the sum of the cathode drops of the series arcs, and second, to the effective projection of the arc against efficient cooling surfaces resulting in rapid deionization of the arc stream.

The chart illustrated on figure 11 gives a comparison of the arcing times of a conventional open-break type of air circuit breaker tested without an enclosure and an enclosed air circuit breaker equipped with "pin type" arc quenchers. It may be noted that the arcing time of the former is quite erratic even when tested in the open, where the enclosed "pin type" breaker interrupts consistently over a wide current range in two half cycles or less. Operation of this sort greatly reduces the stress on the equipment to be protected and contributes materially to the safety of the operating personnel. Table I shows data from interrupting tests conducted on a 6,000-ampere air circuit breaker, equipped with pin-type arc quenchers, at 600 volts, three phase, up to and including a maximum current of 125,000 amperes. It is to be noted that the arcing times are one-half cycle or less, and indicates definitely the consistent performance of this type of interrupter. Figure 12 shows an oscillogram of the maximum current interrupted during this particular test series.

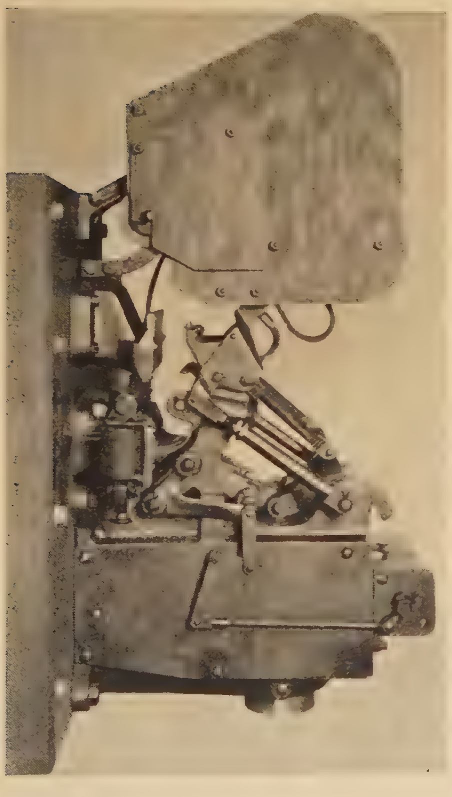


Figure 8. Modern magnetic-blowout type of air circuit breaker

Table I. Data From Three-Phase Tests on a Type AL-2, 6,000-Ampere Air Circuit Breaker Equipped With "Pin Type" Arc Quenchers

Duty—O; Test—600 Volts, Three Phases, 60 Cycles

Current (Amperes), Maximum Loop: Peak Value	Current (Amperes), Maximum Loop: Root-Mean-Square Value	Duration of Short Circuit (Half Cycles)	Arc Duration (Half Cycles)
52,000	30,000	7.0	0.9
59,000	34,000	7.1	0.7
79,000	46,000	7.1	0.7
103,000	62,000	6.4	0.5
128,000	76,000	6.7	0.9
83,000	50,000	6.7	0.7
125,000	76,000	6.0	0.8
116,000	78,000	6.4	0.8
137,000	80,000	6.4	0.7
166,000	100,000	6.0	0.8
245,000	142,000	5.9	0.5
192,000	114,000	5.8	0.7
192,000	119,000	5.5	0.7
210,000	134,000	5.7	0.7
220,000	130,000	5.6	0.6

In figures 13 and 14, typical breakers equipped with pin-type arc quenchers for interrupting ratings of from 10,000 to 80,000 amperes are shown. The introduction of such devices constitutes a major step in the art. Experience during the past three years, since these interrupters were introduced to the field, has indicated a very satisfactory performance. Needless to say, due to the efficient way in which these interrupters control the arc, outward objectionable disturbances such as noise, hot arc gases, and other volatile arc products have been greatly reduced, so much so that typical steel-enclosed breakers of this type manifest no outward disturbance even when tested at their full interrupting ratings.

General Structure

Figure 15 illustrates a more recent trend of air-circuit-breaker construction. Heretofore, the majority of air circuit breakers have been of the manually operated type. Recently, however, there has been a decided increase in the use of air circuit

Figure 9 (below). Oscillogram of high-current test on modern magnetic-blowout type of air circuit breaker

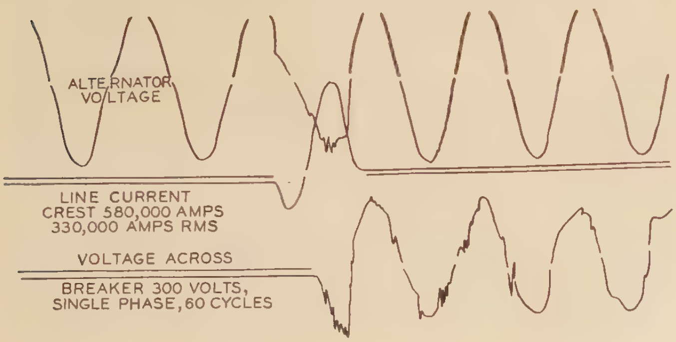
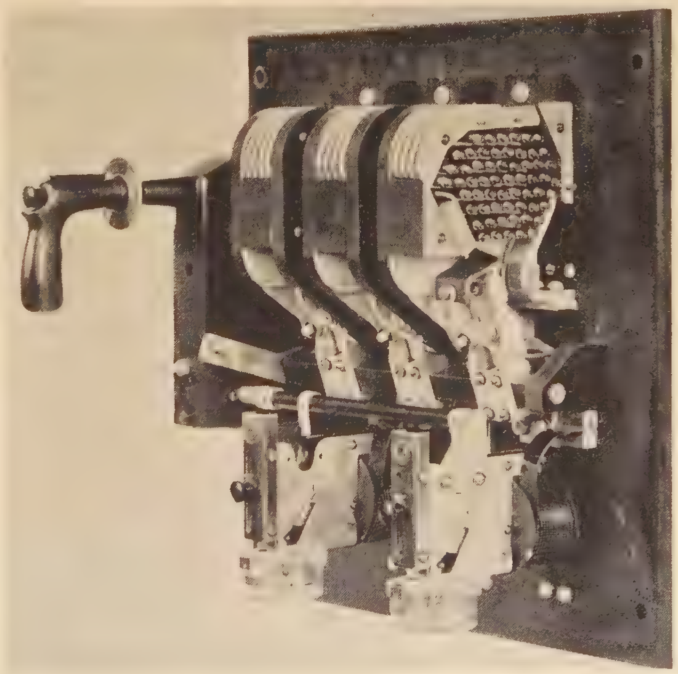


Figure 10. Typical pin-type arc-quencher construction



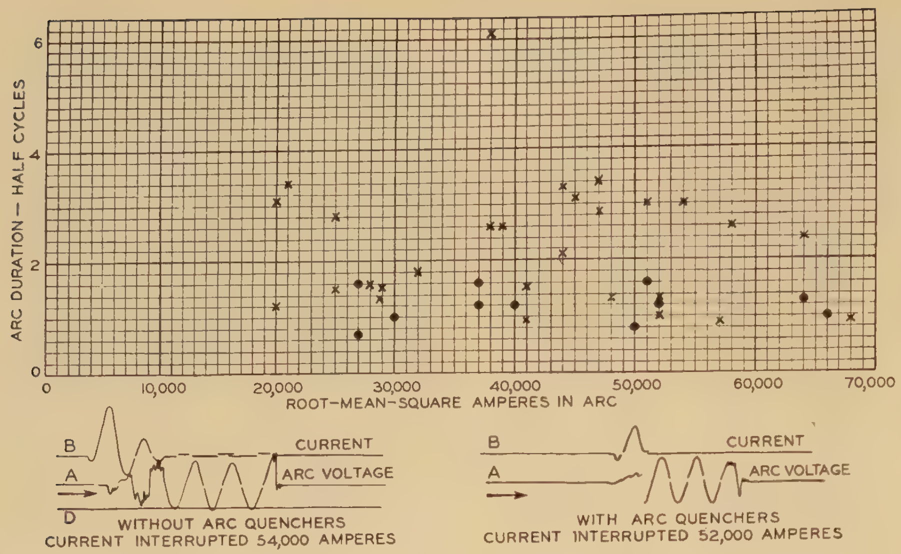


Figure 11. Comparison of arcing times on an open-type carbon-break air circuit breaker and an enclosed air circuit breaker equipped with pin-type arc quenchers

Type *AL-2* air circuit breaker, 600 volts, 1,200 amperes, interrupting rating 40,000 amperes

Crosses—Tests at 600 volts, single phase, plain break, open

Circles—Tests at 600 volts, single phase, with arc quenchers

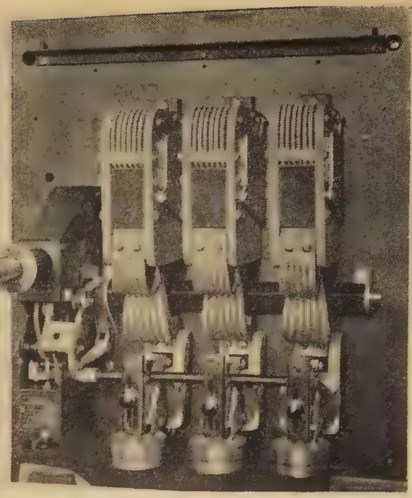


Figure 13. Modern small air circuit breaker equipped with pin-type arc quenchers

breakers which can be operated satisfactorily from a remote point. The generally accepted practice for coping with such a requirement has been to equip an air circuit breaker of the manually operated type with a separate electrical mechanism which, while perfectly satisfactory from an operation standpoint, requires a considerably larger space for mounting. As this trend is associated, however, with the increased use of steel-enclosed air circuit breakers, it is obviously a considerable handicap to increase the size of such steel enclosures merely to provide the necessary additional room for the electrical operating mechanism. To meet this demand without sacrificing space, there has been developed the air circuit breaker structure as shown in figure 15. These latest air circuit breakers require exactly the same space for either manual operation, or electrical operation. This is obtained by simply applying either a suitable manually operated unit or electrical operated unit to the main body of the air-circuit-breaker mechanism. As can be readily realized, this type of construction has met with considerable favor in the field and is, we believe, indicative of the general trend in all future designs.

Summary

From the foregoing, it is evident that considerable progress has been made in increasing the general usefulness of low-voltage air circuit breakers. We have described the evolution from an adapted knife-switch device up through the years to the present-day air circuit breakers

Figure 12. Typical oscillogram of an interrupting test on a 6,000-ampere air circuit breaker equipped with pin-type arc quenchers

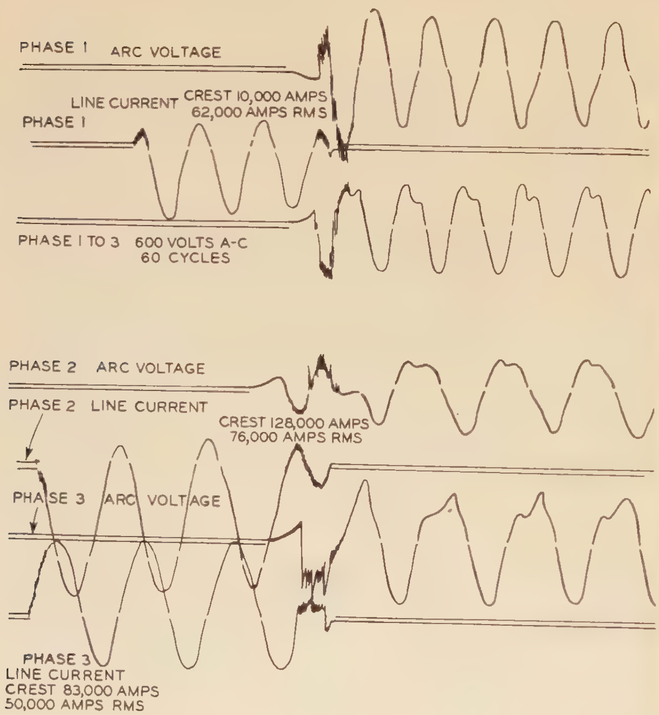
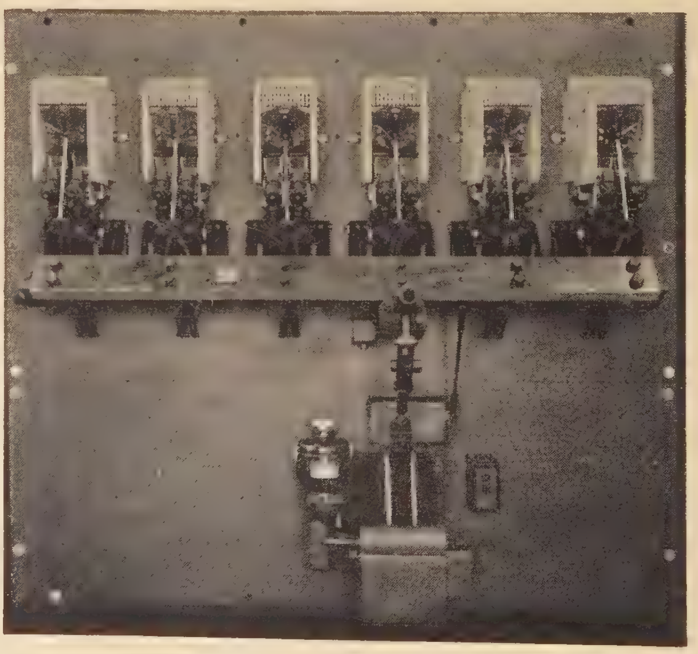


Figure 14. Modern large air circuit breaker equipped with pin-type arc quenchers



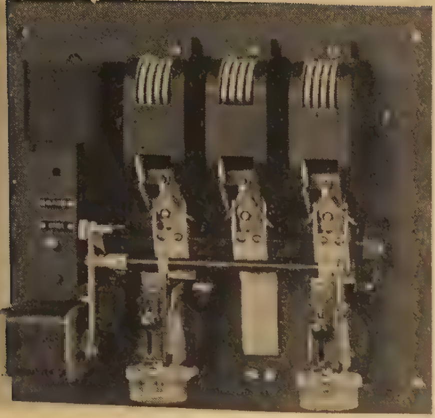


Figure 15. Modern electrically operated air circuit breaker

applicable to all low-voltage power and lighting circuits where continuity of service, safety of operation, and low maintenance are desired. The development of the solid-silver line-contact construction has contributed materially to the increased speed of operation, reliability of service, and reduction of size which are such paramount factors today. The pin-type arc quencher is a material contribution to the safety of personnel and protection of equipment, and its performance renders possible the use of air circuit breakers in steel-enclosed compartments without impairing the interrupting ratings.

Discussion

A. E. Anderson (General Electric Company, Philadelphia, Pa.): Mr. Seaman has described certain developments that have taken place in order to produce low-voltage air circuit breakers having improved performance features, such as low maintenance, improved current-interrupting performance, together with reduction in weight and space requirements.

Any improvement in the design of the main current-carrying parts, which will result in reduced maintenance and increased continuity of service, is a step in the right direction. However, the question frequently arises as to the necessity of circuit breakers of interrupting ratings in excess of 40,000 amperes. A rule of thumb that has been quoted many times is that it is difficult, if not impossible, to obtain currents in excess of 20,000–40,000 amperes on circuits up to 600 volts alternating current, due chiefly to the presence of contact or arc resistance. Experience has shown that it is possible to obtain currents in excess of this value.

Outside of machine characteristics, the factor of resistance is the only one that appears in connection with d-c circuits and there seems to be no question that very large currents are possible and values in excess of 200,000 amperes at 600 volts have been obtained. The resistance found in such circuits during fault conditions is exceedingly low. Accordingly, due allowance has been made in selecting circuit breakers for such applications.

As far as a-c circuits are concerned, we must consider in addition the reactance of the external circuit and that of the generating or transformer equipment. The per-unit reactances of low-voltage generators are usually considerably less than those in the higher-voltage machines, thus tending to increase proportionately the value of short-circuit current. Also, the reactance of low-voltage conductors is less than that of higher-voltage conductors due to decreased spacing. Looking at this from the voltage-regulation standpoint, it would be expected that the allowable maximum regulation would not exceed ten per cent for satisfactory operation of motors and other apparatus. Accordingly, the short-circuit current available at the time that the circuit breaker opens would be at least ten times the continuous-current rating of the circuit. This result takes into consideration the circuit resistance as well as the circuit reactance.

In the case of switchgear, the maximum short-circuit current is obtained in the vicinity of the circuit-breaker terminals, which means that only the connection copper, busses, cables, and other primary circuit apparatus between the point of short circuit and the generator or transformer should be taken into consideration. Generally speaking, less than ten per cent of the total impedance of this part of the system is found in the cable or apparatus external to the generator or transformer. In fact, this impedance is usually so low that it can be neglected. A further consideration shows that the resistance component of this impedance has a minor effect on the calculated result. The use of silver at the various points of contact in the switchgear, further tends to reduce this factor. Faults some distance from the switchboard, such as at the end of feeder cables, or at some group bus supplying motors or other apparatus, will usually result in lower short-circuit current due to the relatively higher impedance of these smaller cables.

This then leaves the item of arc resistance and its contribution to the over-all result. An open arc is a random affair. Mr. Seaman's paper brings out the design features in a circuit breaker that have to be taken into consideration in order to control the arc and keep it confined within a restricted space.

As the installation becomes larger, a greater amount of short-circuit current is developed and a greater space would be required for the interruption of any free or open fault arc. The spacing of conducting parts at the rear of the switchboard does not permit this arc to expand to the extent that its resistance would have an appreciable effect, or to reduce the current to one-third or one-half of its calculated value, which would sometimes be required in order to limit its value to 40,000 amperes as mentioned above. Therefore the effect of resistance of any open or free arc that might be obtained on the circuit is omitted in calculating the short-circuit current.

The mechanical and thermal requirements of current transformers, connection copper, and associated apparatus must also be taken into consideration. For example, the bus may not only be required to have a rating as high as 10,000 amperes, or more, but may have to withstand stresses imposed by fully offset values greater than 200,000 amperes root-mean-square. This part of the application brings in the stress set up by the electromagnetic forces, coupled with vibration at fundamental and harmonic frequencies, due to resonance between bus, supports, and the frequency set up by the electrical system.

Modern practice calls for an enclosed type of circuit breaker. This feature provides a safe and compact installation and, in one variety of switchgear, a design that permits ready means for withdrawing the unit for inspection or maintenance. The circuit breaker is so interlocked that it must be in the open position before it can be connected to or disconnected from the bus. The smaller units are arranged vertically, usually three high. The larger and heavier units are mounted on one level only and rolled into position.

Units of this kind have been applied to motor, generator, transformer, lighting, station auxiliaries, and other loads. Provisions are included to facilitate shipment and installation, as well as to permit future expansion. The latter possibility should include a consideration of the maximum amount of generating or transformer capacity in order to meet the short-circuit requirements that may arise in the future.

D. C. Prince (General Electric Company, Philadelphia, Pa.): From time to time the question has been raised whether it is necessary to have interrupting ratings of air circuit breakers of the order of 40,000/60,000 amperes or more where these circuit breakers are installed on 440- or 600-volt circuits. It has been contended that even though calculations might show such currents could exist, actually in practice they would not, and, therefore, discount factors have been employed, and smaller circuit breakers have been installed than those bearing the ratings of the calculated maximum short circuit. There was a feeling for some time that for some reason or other short circuits actually obtained did not correspond to calculated values. In the last year or two a good deal of work has been done along this line, taking great pains to include in the calculation allowance for all available reactance and resistance, and it is now certain that where the calculation is made with sufficient care, the currents for a bolted short circuit will correspond very closely to the calculations.

The next question raised is whether an actual short circuit occurring in the field may have the properties of a bolted short circuit. It goes without saying that most short circuits will not have such properties. Particularly in calculations involving control apparatus, the short circuits are likely to include considerable cable runs, and when a breakdown does occur, such as between winding and ground in a motor, the fault is likely to have a considerable amount of impedance.

On the other hand, where a switchboard is involved, any fault occurring in the switchgear structure may approach the full value of a bolted short circuit. The question has been raised whether a foreign body such as a copper bar will not be blown clear, say from a bus structure across which

it has fallen, without giving currents of greatest magnitude. Tests of this particular configuration have been made with the result that currents of the order represented by the circuit breaker ratings will blow a solid bar clear but not quickly enough to prevent the current from reaching its maximum value. Even in the switchboard structure, most faults are likely to have less value than the maximum calculated fault. For instance, a short section of control wiring getting across the busses will be fused almost instantaneously and may produce an arc of sufficient length to keep the current well below the maximum possible fault. However, if the calculation has been carefully made, it is certain that the maximum fault current calculated may occur, and for that reason air circuit breakers should be installed with ratings equal to or greater than the maximum calculated fault if it is necessary to be sure that the fault will be cleared by each breaker in question.

In considering the application of air circuit breakers, however, there is one more point which should be covered. If an oil circuit breaker is incorrectly applied and is stressed beyond its capacity and fails to clear, serious damage may result. The circuit breaker may burst, allowing the escape of oil, which may produce secondary damage of considerable magnitude in addition to the loss of the breaker itself. An installation of oil circuit breakers under conditions where the maximum fault is known to be beyond the circuit breaker capacity may represent a real hazard and not merely a business risk. On the other hand, if an air circuit breaker is placed in a circuit where the maximum possible short circuit may exceed its interrupting ability, the circuit breaker itself may be burned up, but secondary damage is likely to be of a relatively minor character.

It has been found that where a number of small circuit breakers are backed up by one larger one, which is free to trip instantly in the event of a heavy short circuit, the cascade combination will satisfactorily clear a fault up to the capacity of the larger circuit breaker. Tests have been made to verify the range in sizes for which the smaller breaker will be protected. With these factors in mind, it is possible to design a distribution system including various sizes of air circuit breakers, the smallest of which are of a rating less than the maximum short circuit which they may be asked to clear. In the unlikely event that such a short circuit does occur, it should not be necessary to replace the particular small circuit breaker involved, but even if the smaller breaker is damaged, this may be regarded as a legitimate business risk. In such an installation, of course, there must always be some circuit breakers of adequate capacities to take care of any fault which may possibly occur, and of adequate speed of operation to afford some real protection to the smaller breakers. Air circuit breakers are available which have these characteristics, proved by actual tests, both free and in enclosures, sufficient to meet the most exacting demands.

In past times, the application engineer has faced the dilemma that if he recommended large enough capacities to be safe, his installation was uneconomical, while a recommendation, sound from an economic point of view, was hazardous to both life and property. With knowledge of the new air circuit breakers, he can, by suitably selected and proportioned backup protection, secure a practical solution of this problem. Small air circuit breakers protect utilization equipment from all but the exceptional faults at a minimum of cost. Master breakers of adequate rupturing capacity back up the first line and protect both equipment and small breakers from the exceptional fault.

Special Problems of Two-Pole Turbine Generators

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THE two-pole turbine generator differs from similar generators with a higher number of poles, in that the mechanical rigidity of the rotor body varies from a maximum value on the pole axis to a minimum value on the winding axis, and the stator core is subjected to radial magnetic forces on only one diameter corresponding to the axis of the resultant magnetic field.

The unequal mechanical rigidity of the rotor body on the two major axes results in a variation in the static deflection of the rotor as it rotates. This variation in the deflection occurs at a frequency equal to twice the rotating frequency and acts as a double-frequency vibratory force in causing the rotor to vibrate.

The unequal magnetic forces on any two major axes of the stator core cause it to distort and take an elliptical shape, with the short axis of the ellipse coinciding with the axis of the air gap magnetic field. The distorting magnetic forces rotate with the rotor and thus produce a stator core distortion which rotates at synchronous speed. Since the elliptical shape rotates with the rotor, the resulting vibratory motion of any point on the stator core has a frequency twice that corresponding to the rotating speed.

These rotor and stator double-frequency vibratory forces and resultant vibrations are present in every two-pole generator irrespective of rotational speed or physical proportions. The vibration is more pronounced in the case where the frequency of the forces is approximately equal to the resonant frequency of the part in question. The effects are relatively small in 25-cycle units due to the fact that the frequency of the disturbing forces is low with respect to the resonant frequency of the generator and foundation parts. They are also negligible in small-capacity 3,600-rpm generators because of the relatively small double-frequency magnetic forces involved. Double-frequency stator vibrations have been observed on two-pole 60-cycle generators for ratings of 18,750 to 20,000 kva. Both types of double-frequency vibrations become of increasing importance for 60-cycle 3,600-rpm units of relatively large capacity. In such units of larger capacity, the double-frequency vibratory forces are transmitted to mechanically connected associated apparatus, bearing supports, foundations, and station structural parts, and result in objectionable vibrations and noise.

It is the purpose of the present paper to discuss the general problems of double-frequency rotor and stator vibrations of two-pole generators and present methods by which the disturbing force producing the vibration can be eliminated or the vibration restricted to specific isolated parts.

Double-Frequency Rotor Vibration

The general problem of 3,600-rpm-generator double-frequency rotor vibration due to unequal mechanical rigidity on the two major axes of the rotor was investigated by the writers in 1928 and 1929. Rotor models, dynamically similar to the rotors for the largest 3,600-rpm generators which were then contemplated for the future, were made. Running tests were made on the models over a speed range from zero to 4,500 rpm, and vibration measurements were made for

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the entire speed range. The following facts were obtained:

1. The models vibrated with quite large amplitudes at rotating speeds corresponding to one-half their fundamental natural frequencies. The frequency of the vibration was twice that of the rotation of the models.

2. The double-frequency vibration persisted throughout the entire speed range and it was not influenced by changes in the balance of the models.

3. The models were found to have two fundamental natural frequencies corresponding to the two principal rotor rigidities. These critical frequencies were about 50 rpm apart and were less than one-half the normal operating speed of 3,600 rpm. The vibration of the models throughout this 50-rpm speed range was unstable, that is, the amplitude of vibration would steadily increase when the speed was held constant.

4. The single-frequency vibration predominated throughout this 50-rpm speed range and over this speed range the models were quite sensitive to the amount of unbalance present.

The following conclusions applying to large-capacity 3,600-rpm generators were reached from a study of the data obtained from the model tests:

1. The internal damping in the rotor body of an actual generator due to the friction of the conductors on the coil slot sides was considered to be sufficient to ensure stable operation of the rotors throughout the total speed range.

2. Rotors of the length in question were known to be more difficult to balance than the shorter, more rigid ones, but it was thought that with proper care being given to the placing of the balance weights along the axis of the rotor, the job could be done without difficulty.

3. It was realized, before the model tests were made, that the double-frequency vibration would persist throughout the speed range of the rotor, but no trouble with it was anticipated because of the great difference in speed between one-half the first critical speed and the normal operating speed.

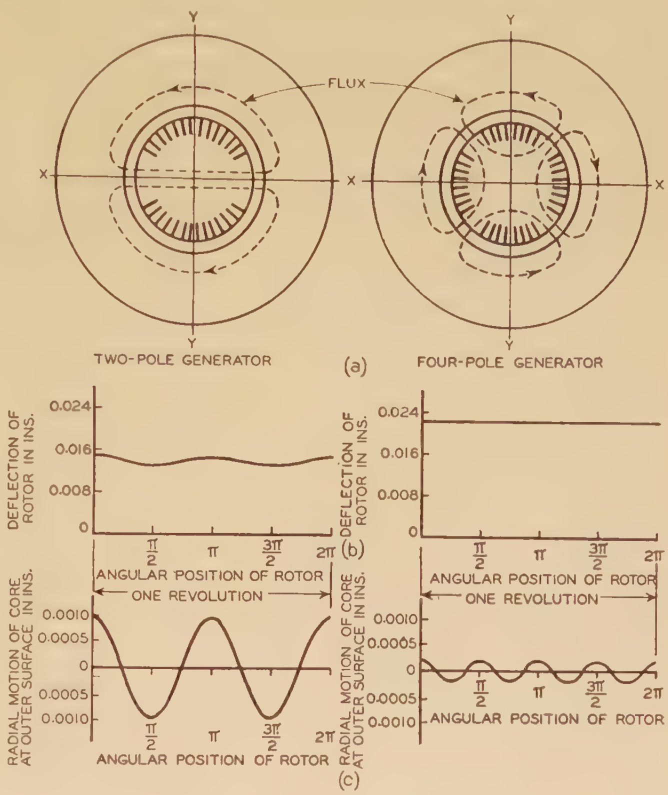
Since these tests were made, 3,600-rpm turbine generators have been built with conventional rotor designs for ratings of 43,750, 50,000, and 58,750 kva. The running performance of the rotors of these generators has demonstrated the accuracy of our predictions as based on the model tests. In no case did any of the above rotors give evidence of instability or excessive vibration at either the fundamental critical speed or at the subcritical speed equal to one-half the fundamental. The rotors were more difficult to balance, but with the more accurate balancing equipment now available, this was accomplished satisfactorily. Two of the above rotors were entirely satisfactory in regard to double-frequency rotor vibration at full speed. The magnitude of the double-frequency vibration in the rotor of the 58,750-kva generator, although acceptable, was somewhat higher than originally anticipated. Corrective action may be taken on this rotor at a future date to reduce the magnitude of the double-frequency vibration.

It was originally anticipated that two-pole 60-cycle generators above 62,500 kva would necessitate changes in the rotor design adequately to take care of the double-frequency forces and vibrations

A first natural suggestion might be to provide flexibility in the bearing supports so that the vibratory forces would not be transmitted to the foundation, station parts, and other equipment. This type of corrective measure can be considered to be only partial solution at best, even though it were 100 per cent effective, since it permits the rotor shaft ends to move freely and thus transmit the double-frequency motions to the collector rings, couplings, and coupled apparatus. The effects of double-frequency vibrations on these parts are of equal or greater importance than on foundation and station equipment.

A second and more fundamental method of solving this problem is to equalize the mechanical rigidity on the two major axes and thus reduce the double-frequency disturbing forces to values of inappreciable magnitude. There are two methods of equalizing the mechanical rigidity on the two major axes. One is to machine annular grooves in the rotor body to such depth that the additional rigidity contributed by the pole sectors and rotor teeth will be inappreciable. This is not a feasible method for two-pole 60-cycle generators due to the fact that the rotor diameters are inherently small and the provision of annular grooves of appreciable depth would result in an intolerable flexibility of the rotor. A second and more feasible method is to reduce the rigidity on the pole until it is essentially equal to the combined rigidity of rotor teeth and field coils on the winding axis. This can be accomplished by machining longitudinal or transverse slots in the pole body. If longitudinal slots are used, it is necessary to remove an appreciable percentage of the pole material to get the necessary change in rigidity. Thus, in order to avoid too much saturation and a reduction of the magnetizing flux in the pole body, it is necessary to replace the removed material with magnetic filler bars in the machined slots. The use of transverse slots in the pole body is the most effective method of obtaining a required reduction in rigidity with a minimum amount of material removed. Narrow, segmental-shaped, transverse

Figure 1. Diagrams illustrating comparison of two-pole and four-pole turbine-generator rotor and stator vibration



grooves can be provided in the pole body to accomplish the desired results without intersecting the winding slots and without removing an amount of magnetic material which would upset the magnetic saturation conditions. Both of these methods of equalizing the rigidity on the two major axes of two-pole generators are covered by United States Letters Patent number 1,994,922, which was issued in 1934.

Transverse, segmentally-shaped rotor body grooves have been applied to two-pole 3,600-rpm generators for ratings ranging from 20,000 to 58,750 kva to equalize the mechanical rigidity on the two major axes. This change made more feasible the problem of machining the shaft journals, collector rings, and couplings to true cylindrical dimensions. It also simplified the rotor-balancing problem, and practically eliminated the double-frequency rotor vibrations. This construction is now standard for all two-pole 60-cycle generators for ratings of 18,750 kva and above.

Double-Frequency Vibration of the Stator Core

The stator core of a turbine generator consists of layers of segmental steel laminations arranged in complete circles in a supporting frame structure. The stacked laminations are maintained under pressure in the axial direction by means of bolts and heavy end plates which are anchored to the stator frame. The contact pressure between laminations is so high that the friction forces between laminations are of such magnitude as to ensure that the built-up stator core acts as a solid steel cylinder in resisting distortion. The stator core is maintained in a fixed circumferential position with respect to the frame structure by means of dovetail keys or projections. Since the stator punchings are stacked in the stator frame with normal building clearances, it is obvious that the frame structure can contribute little or no rigidity to the stator core in resisting distorting forces. However, there is sufficient mechanical contact between the two members to permit the transmission of vibratory forces from the stator core to the frame structure.

There has been a wide variation in the amount of vibration and noise emitted from large-capacity 3,600-rpm generators of duplicate design and for units of different ratings, but using the same stator punchings. It is believed that the amplitude of vibration of the stator cores is essentially the same for all such cases and that the variation in frame vibration and noise is due to differences in the effectiveness of the mechanical coupling between the respective frames and cores, due to building variations. Vibration measurements have been made on the stator cores of such machines when operating over the complete load range, and the magnitude of the motions is no greater than experienced on lower speed machines. It is not believed that the present double-frequency vibrations existing in stator cores of two-pole 60-cycle generators will result in any undue deterioration of the stator core, winding, insulation, slot wedges, and main leads.

Since both the double-frequency disturbing force and the elliptical type of core vibration are inherent with the two-pole generator, the cause of the vibration cannot be eliminated. A first-thought solution would be to reduce the magnitude of the vibrations by reducing the air-gap magnetic density and by increasing the rigidity of the core to bending. If drastic changes were made in both items to give a combined change of 100 per cent, the vibrations would be reduced approximately 50 per cent and would still be transmitted in the conventional generator to the stator frame, foundation, and other station parts. The cost of the generator would be increased approximately 75 per cent and the manufacturer and purchaser would both still be confronted with the problem of determining whether a 50 per cent reduction in the amplitude of the vibration would be satisfactory. On the basis of the present data and operating experience available on large two-pole 60-cycle generators, it is felt that the results obtained would not be acceptable and the generator could not be justified economically. Since the magnitude of present stator-core vibrations is not considered deleterious to the life and performance of the generator, a more logical and economical solution would be to isolate the stator core and reduce the magnitude of the disturbing forces transmitted to other parts.

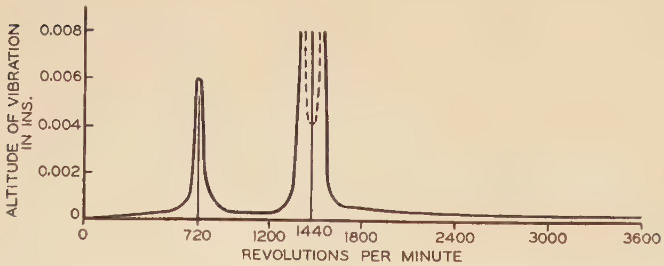


Figure 2. Vibration curve of unsymmetrical rotor

A mathematical analysis was made by J. G. Baker, formerly of the research department, Westinghouse Electric and Manufacturing Company, to determine the motion of any point in a freely supported two-pole turbine-generator stator core when subjected to a rotating diametrically applied distorting force. The essential results of this analysis are as follows when considering the stator core as a curved beam:

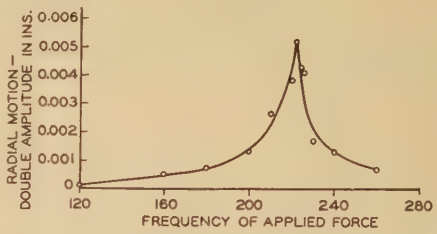


Figure 3. Resonance curve for stator core

(*a*). The path of a point on the neutral axis of the stator core is an ellipse, the major axis of which is radial and twice the length of the minor axis.

(*b*). For points at a larger radius than that of the neutral axis, the tangential motion decreases as the radius is increased. At a distance beyond the neutral axis equal to one-third the radius of the neutral axis, the tangential motion is zero, and the motion is purely radial.

(*c*). For points at a shorter radius than that of the neutral axis, the tangential motion increases as the radius is reduced and the path of a point in the tooth zone is approximately circular.

(*d*). The maximum change in the dimensions between adjacent teeth is only 10 to 15 per cent of the radial motion at the back of the core.

In order to check the calculated characteristics of the stator-core vibration and determine methods to prevent the transmission of vibratory forces from the stator core to other parts, a complete experimental investigation was made on a full-size generator model. The model consisted of a stator core 16 inches long built from standard laminations used in the construction of the largest 3,600-rpm generators, a stationary laminated rotor member to complete the magnetic circuit, and a flexibly connected ring-type

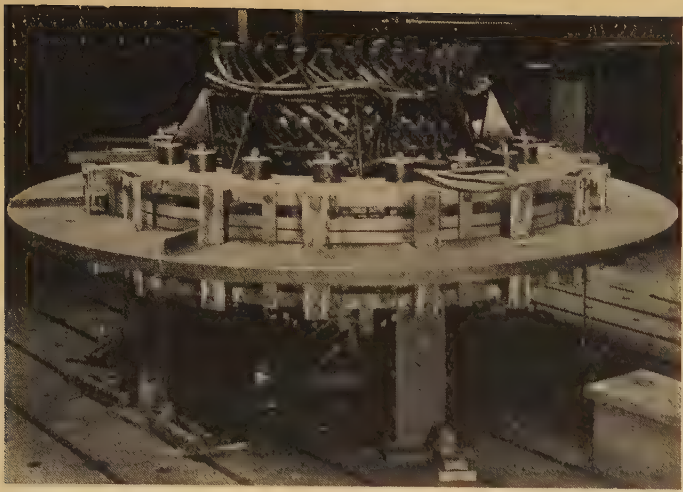


Figure 4. Model of stator core for 3,600-rpm turbine generator

frame member. A two-pole three-phase winding was provided in the stator core and was supported in the slots by slot wedges installed in the conventional manner. The model was mounted with the axis in the vertical direction in order to simplify and reduce the cost of the assembly. The flexible ties between the stator core and the frame allowed relative radial motion of individual parts of the stator core with respect to the frame, but prevented relative lateral motion. Practically no tangential flexibility was provided in the supports. The stator winding had sufficient capacity to produce a rotating magnetic field in the air gap of 60,000 lines per square inch for any single- or three-phase supply frequency up to 130 cycles per second.

Tests were made to determine the effect of frequency, magnitude of air gap magnetizing flux, pressure between laminations, and the flexibility of supports on the vibration of the stator core and frame housing. The test results showed that the curve of stator-core vibration as a function of frequency had a sharp resonance peak with the natural frequency at 222 cycles per second. Actual vibration measurements at different points on the stator core checked closely with the values obtained by analysis. The reduction in pressure between laminations obtained by relieving the tension on the through bolts had no effect on the vibration performance of the core, although it is believed that this was due to the fact that the punchings were tightly cemented together with varnish and did not loosen when the bolt pressure was relieved.

The vibration data obtained by test and analysis indicates that the radial motion of any point at the back of the stator core is approximately 0.001 inch and the tangential motion is essentially zero. This simplifies the support problem since flexibility is required in only the radial direction. The general type of problem is basically the same as that satisfactorily applied to slower-speed single-phase 25-cycle generators except that in the single-phase generator, the output torque is pulsating at double frequency and tangential flexibility must be provided for the stator-core supports, whereas in this case radial flexibility only must be provided. Test results on the model showed that the use of the flexible stator-core supports decreased the magnitude of the double frequency transmitted to the frame to a small percentage of the value obtained with a conventional assembly.

In order to expedite the solution of the mechanical problems and develop the construction details involved in providing stator-core supports with radial flexibility, this principle of design is being first applied on a 12,500-kva 3,600-rpm turbine generator. This generator will be operated under both load and sudden short-circuit conditions to determine the adequacy and effectiveness of the design in accomplishing the desired results from the standpoint of objectionable noise and vibration.

Summary

Double-frequency rotor vibration due to different rigidity constants for the two major axes in two-pole 60-cycle generators can be eliminated by equalizing the rigidity constants on the two axes. This can be accomplished without introducing any reduction in flux capacity by machining narrow transverse slots in the body of the poles.

The double-frequency vibratory forces inherent in two-pole generator stators cannot be eliminated. It is further believed that acceptable results cannot be economically obtained by reducing the air-gap magnetic densities and increasing the rigidity of the stator core over that normally obtained when magnetic conditions are adequately satisfied. Also the stator vibration is not of an amplitude considered to be harmful; consequently, the most practical solution is to isolate the stator core by means of flexible supports, and thus materially reduce the magnitude of the disturbing forces transmitted to the stator frame, foundation supports, and associated apparatus.

Discussion

M. D. Ross (Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): This paper covers two very important moves to reduce or eliminate vibrations of rotor and stator parts of two-pole generators, which have been present to a certain degree in all machines of this type. These effects are aggravated in the larger two-pole machines and have reached the point where it was desirable to take some steps to reduce them to levels comparable to those in the smaller two-pole machines.

The stator-frame vibration in some of the large machines which have been built has been responsible for considerable 120-cycle noise; whether it is noticeable in the turbine room depends largely upon the number of machines operating in the same room and upon the size and shape of the room. Noise levels in most turbine rooms at the operating floor level usually run from 95 to 100 decibels. This noise is made up of a large number of frequencies and usually varies markedly from one point to another due to reflections of sound waves from turbine-room walls and floor. Reducing the vibration of the generator frame as outlined in this paper will reduce the generator noise, but may not greatly reduce the noise level reading of the room due to noises from other sources.

It would, therefore, seem logical to consider using sound-proofing material on the walls and ceiling of the turbine room, to absorb the noise and reduce the over-all noise level in the room. The average turbine room with its hard walls and floor has very low sound-absorption properties. When a large total sound energy is released in such a confined space, the noise level is considerably increased due to the reflections from the walls. If, on the other hand, the walls had high absorptive properties, the reflections would be largely eliminated. A striking example of this may be noted in the case of a well-known sound-proofed telephone booth in considerable use in turbine rooms. One side of this booth is open to the room, but the noise level inside is low enough to permit satisfactory telephone conversation while this would be impossible outside the booth.

Where sound-proofing of the engine room has been tried with Diesel engines, we understand the reflected sounds have been practically eliminated. It would seem that this factor should be considered in the design of future turbine rooms. With such moves as described in this paper to reduce noise at its source and a related move to reduce the effect of such noise as remains in the room, a much more satisfactory installation could be obtained.

H. D. Taylor (General Electric Company, Schenectady, N. Y.): The authors' observations regarding double-frequency rotor vibration agree for the most part with tests made by the writer and described in the ASME paper to which they refer. One exception may be mentioned that in our tests the double-frequency rotor vibration did not persist throughout the entire speed range, but was found to be small at the main critical speed, and entirely negligible at running speed.

With regard to the suggestion that internal damping in the rotor bodies of large turbine-generators might be sufficient to overcome the tendency toward instability at the main critical speed, it has always been the writer's understanding that internal or "rotating" damping was an extremely undesirable property for high-speed rotors, in that it tends to promote "whipping" or nonsynchronous vibration at the critical frequency when operating above the critical speed. This tendency is entirely apart from the promotion of similar vibration by the oil film in journal bearings at speeds of about twice critical or higher, although the two may both be present and add their effects.

The running performance of some 15 or 20 large 3,600-rpm generators from 25,000 to 66,667 kva placed in service by the General Electric Company in the past two or three years has failed to disclose any difficulty due to unequal mechanical rigidity of the rotor body. The subcritical has in general been barely discernible; the main critical has always yielded satisfactorily to balancing operations; and at running speed, the double-frequency vibrations have been so small as to be entirely harmless.

Magnetic vibration of the stator core and frame structure, however, appearing when excitation is applied, has been a real problem. All of these machines have exhibited this form of double-frequency vibration in greater or lesser degree. Contrary to the authors' experience, we have found the amount of vibration *on the machines themselves* to be very consistent on machines of similar design. The amount of noise resulting from this vibration has varied widely, depending on at least two sets of conditions: (1) the presence or absence of adjacent structures responsive to 120-cycle stimulation, serving as "sounding boards," and in a number of cases producing a great deal more noise than the generator itself; (2) the acoustic properties of the turbine room, which may promote reflections and reverberations of the radiated sound waves in such a way as to amplify the general noise level.

We have made a study of the design factors affecting the magnitude of this magnetic vibration, and, on the basis of analysis and test data, have concluded that a very definite and desirable reduction can be obtained economically by increasing the rigidity of the core. Reductions of the order of two to one can be had, we believe, with only a small increase in the cost of the generator, of the order of 5 per cent or less. The authors' point as to whether this amount of reduction will be satisfactory is well taken. We have made tests in one customer's plant in which the generator voltage was reduced to a point where the noise became unobjectionable, and the corresponding reduction in vibration amplitude was found to be just two to one. This, we realize, may not hold in all cases. For the past year, however, all our new designs for large 3,600-rpm machines have had the core structure stiffened to reduce magnetic vibration; one of these machines has recently gone through factory tests, and shows a very gratifying improvement, meeting our expectations fully.

As a further step to take care of cases which may need a greater reduction, we have also been developing an elastic mounting of the core structure inside the frame, for the purpose of isolating the remaining vibration at its source. Our analysis and tests have both indicated that, even on a core of great radial depth, the tangential vibration at the outer diameter may not be negligible, and we feel therefore that it is desirable to provide both tangential and radial flexibility in the core supports.

Sterling Beckwith (Allis-Chalmers Manufacturing Company, Milwaukee, Wis.): The papers by Snell, Ross and Sterrett, Laffoon and Rose, and Mortensen and Ryan are all closely related, and will all be discussed together.

The use of hydrogen in condensers and frequency changer sets is not new, nor is its use in small experimental turbine generators new. However, the spectacle of at least a dozen large turbine generators all about twice as large as the largest previous machines and all on order and designed for hydrogen by three different companies before a single one was in operation is exceedingly unusual and interesting.

One of the first things noticed about a hydrogen-cooled machine is the additional piping and control necessary above that required for an air-cooled machine. A large part of this apparent complication is due to three factors. The first is the control circuit, but if this circuit is compared with other station control circuits, it will be found to be relatively simple. The second factor is the hydrogen-control piping which is perhaps somewhat complicated in its entirety, but since most of it is used only at very rare intervals when the hydrogen is admitted to or exhausted from the generator, its operation is not a problem. The third factor is the oil-supply and vacuum-treating equipment, but as a second supply is provided so that shutdown of the vacuum-treated supply is permissible, the reliability of the machine as a whole is not greatly affected by the added complications of the oil-supply system.

Some of the complications are perhaps unnecessary, and may be eliminated in the future. The relief valve, for example, is hardly necessary since the duration of any explosion would be too short for it to afford any relief of pressure in the machine, and secondly the complete failure of the hydrogen-supply control valve which may admit a cylinder or more of hydrogen to the machine would not necessarily produce dangerous pressures. Furthermore the alarm system gives an immediate indication of excessive pressures in the machine.

When a hydrogen-cooled machine is in operation, its extreme quietness compared with other 3,600-rpm machines is very apparent. This is due chiefly to the heavy weight of the explosion-proof housing, and the absence of flat panels in its exterior walls, as it would be quiet with air as well as with hydrogen.

In operating at high hydrogen pressures to obtain increased generator output, hydrogen leakage through the housing will vary very nearly in proportion to the square root of the pressure. Consequently a normal leakage of 30 cubic feet a day at four inches of water will become about 300 cubic feet per day at 15 pounds pressure. Such a large leakage may not be justified for continuous operation, but could readily be justified for short time or emergency overloads.

Critical speeds of a two-pole rotor have an additional subharmonic because of the lack of slots near the center of the poles. This is shown in figure 3 of the paper by S. H. Mortensen and J. J. Ryan, and in figure 2 of the paper by C. M. Laffoon and B. A. Rose. That one machine only should cause trouble from this source, as mentioned in the second of these articles, is somewhat unexpected and leads one to wonder how such other possibilities as forging dissymmetry and foundation variations can be eliminated. The writer's experience with several large machines has indicated no difficulty from the unequal moments of inertia.

B. A. Rose: Mr. Taylor is correct in his statement that internal damping in a shaft tends to promote nonsynchronous vibration at the critical frequency when the rotor is operating above the critical frequency. The statement in the paper to which this point refers is a little misleading in that it should have referred to operation at the critical speed only. On the other hand, the Westinghouse company has encountered no trouble with its 3,600-rpm generator rotors from this cause, even though most of them are designed to operate above their critical speeds.

Mr. Taylor further states that the General Electric Company have experienced no trouble with double-frequency rotor vibration on any of their large-capacity 3,600-rpm machines. The writers believe this can be explained by the fact that the machines in question have no rotor critical frequencies near 120 cycles per second. We have found that our ability to calculate the critical frequencies for the mode of vibration in question is not sufficiently accurate to rely on it for this purpose and have found that the elimination of the nonuniform rigidity is a more positive means of avoiding the trouble.

We are pleased to observe from Mr. Taylor's discussion of the stator vibration problem that, in general, his experiences and theories concerning the phenomenon agree with ours. Their method of providing a flexible core support when announced probably will differ in its detail construction from the one described but will accomplish the required isolation of the core from the frame structure and foundation.

The Hydrogen-Cooled Turbine Generator

D. S. SNELL
ASSOCIATE AIEE

HYDROGEN cooling for electrical machinery was first proposed to the industry through an AIEE paper presented in 1925.[1] The first hydrogen-cooled machine to be placed in commercial service was a 12,500-kva synchronous condenser, installed in 1928.[2] This was followed by other machines of this type, and later, the hydrogen-cooled frequency-converter was introduced. There are now in operation in the United States 20 of these two types of hydrogen-cooled machines, with a combined output of over one-half million kva, and their records of performance have been highly satisfactory. Prior to 1937, the application of hydrogen cooling to turbine generators had been confined to developmental machines in the manufacturers' plants, although several air-cooled generators had been built with provision for later adaptation to hydrogen cooling. In October 1937 the first hydrogen-cooled generator built for commercial service was placed in operation at Dayton, Ohio. This was a 3,600-rpm unit, of General Electric manufacture, rated at 31,250 kva at 0.8 power factor. Since then, a total of 10 hydrogen-cooled generators have been placed in service in various parts of the country, and 27 others are in the course of installation or construction. The total capacity of these 37 generators is over 2,000,000 kva, and their sizes range from 17,000 kva to 81,250 kva at 3,600 rpm, and from 75,000 kva to 176,470 kva at 1,800 rpm.

Two papers have already been presented before the Institute, in which the development and design work of one large manufacturing company in connection with the hydrogen-cooled generator have been described.[3,4] It is the purpose of the present paper to describe the work of another large company in the commercial development of this new-type machine, and to present some of the results of several months' operating experience with eight of these machines.

Advantages of Hydrogen as a Cooling Agent

These have been stated many times before, and are here mentioned only in the interest of completeness.

1. Windage and ventilation losses in hydrogen are only about one-tenth of their value in air, due to the lower density of hydrogen.

2. The rating of a machine can be increased approximately 20 per cent for a given amount of active material, by operation in hydrogen instead of in air, due to the superior cooling properties of hydrogen.

3. The life of the winding insulation is increased, due to the absence of moisture, oxygen, and dirt, and to the fact that corona damage is eliminated, in the hydrogen-cooled machine.

4. The fire hazard is eliminated.

The reduction of the windage and ventilation losses of a turbine generator with hydrogen cooling increases the full-load efficiency about 0.7 per cent for 1,800-rpm machines and about 0.9 per cent for 3,600-rpm machines. In figure 1 are shown the estimated net yearly savings with hydrogen cooling for different sizes of generators, corresponding to these increases in efficiency. These savings assume a power cost of 0.3 cent per kilowatt-hour and an operating time of 80 per cent and take account of the cost of the hydrogen and carbon dioxide required for operating and filling. They also assume the installed cost of the hydrogen-cooled generator to be the same as that of the air-cooled generator, which is usually the case. The savings thus calculated are shown to range from about $4,000 a year for a 25,000-kw 3,600-rpm unit to about $20,000 a year for a 160,000-kw 1,800-rpm unit.

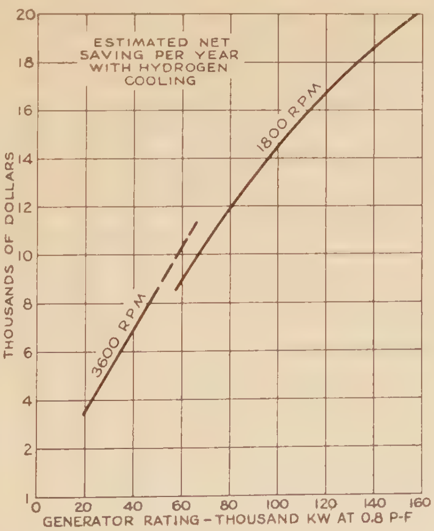


Figure 1. Estimated net yearly saving by using hydrogen in place of air as the cooling agent, for generators in different sizes

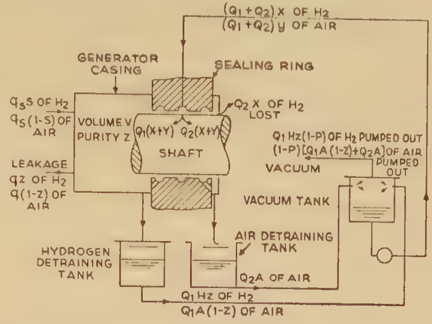


Figure 2. Schematic diagram of shaft-sealing system for hydrogen-cooled generators, using vacuum-treated oil

The greater output per pound of material obtained with hydrogen cooling, extends the limit of output of generators of the 3,600-rpm type and allows the building of generators with self-ventilation in capacities which, if built for air cooling, would require external fans. The largest capacity at 3,600 rpm now considered practicable with air cooling is about 62,500 kva, and such a machine would have external fans; with hydrogen cooling, generators as large as 81,250 kva at 3,600 rpm are practicable, ventilated with internal fans.

Type of Shaft Seal Used

The most important part in the development of the hydrogen-cooled generator was the design of a means for sealing the rotating-shaft extensions against the outward leakage of hydrogen. After investigating many different sealing arrangements, of the mechanical, combination mechanical-and-liquid, and liquid-film types, the General Electric Company finally adopted the liquid-film type of seal for use with its hydrogen-cooled generators. This type of seal is illustrated schematically in figure 2 and includes a sealing ring surrounding the shaft, con-

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The development of the hydrogen-cooled generator described in the foregoing was carried out under the direction of M. A. Savage, and in collaboration with Chester W. Rice, E. H. Freiburghouse, and Robert Hannah. The electrical system of the hydrogen control cabinet was designed by E. J. Flynn and A. J. Bialous. The tests on the Logan and Cincinnati generators were obtained through the co-operation of the Appalachian Electric Power Company and the Cincinnati Gas and Electric Company, which co-operation is hereby gratefully acknowledged.

1. For all numbered references, see list at end of paper.

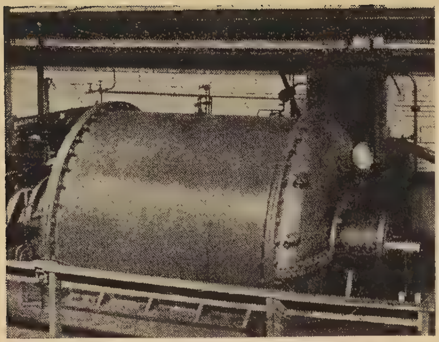


Figure 3. A 6,250-kva 3,600-rpm generator built for operation in hydrogen. Coolers are located beneath the rotor. Vacuum tank for treating shaft-sealing oil shown in background

structed integral with the bearing, to which vacuum-treated lubricating oil is supplied under pressure.[5,6] This creates a film of oil completely surrounding the shaft which prevents the escape of hydrogen from the casing at this point. This type of shaft seal has the advantages of simplicity and ruggedness, and through operating with vacuum-treated oil both permits a high degree of hydrogen purity to be maintained in the generator casing and prevents the contamination of the oil in the bearing lubrication system by the hydrogen.

Tests on a 6,250-Kva Hydrogen-Cooled Generator

In 1926 a 6,250 kva, 3,600-rpm hydrogen-cooled generator was built by the General Electric Company for developmental purposes. This machine, figure 3, was provided with a heavy, cylindrical casing, cast-steel end shields, and with two gas coolers, contained in a rectangular box beneath the rotor. A shaft seal of the oil-film type was provided in each generator bearing. This machine was tested as a synchronous condenser in hydrogen and in air over a period of about 12 months, during which time the operating characteristics of the seals and auxiliary equipment could be observed and information on the heating of the machine in hydrogen and in air obtained. The more important of the heating data obtained in the tests are summarized in figures 4 to 6.

Figures 4 and 5 give the field and armature heating characteristics of the 6,250-kva generator for different loss intensities on the coil surfaces, with air, carbon dioxide, and hydrogen as the cooling media, the tests in hydrogen having been conducted at three different hydrogen pressures. Curves for cooling with helium have been added, based on calculation. The armature heating curves in figure 5 have had deducted the calculated temperature rise of the gas in the air gap due to field I^2R loss. This rise is of the order of from three to five degrees centigrade. This was done in order to use the curves for estimating the armature temperature rise at 0.8 power factor loads, the tests having been made at zero power factor.

The temperature difference between armature copper and between-coil temperature detector for different armature loadings, in air and in hydrogen, is shown in figure 6. At normal load, corresponding to a loss intensity of about 0.3 watt per square inch, this temperature difference is about 15 degrees centigrade in air as compared with 11.4 degrees centigrade in hydrogen at 0.44 pound per square inch pressure. The lower values of the temperature difference at higher hydrogen pressures indicate a slight increase in the thermal conductivity of the insulation at the higher pressures. The crossing of the curves at the higher armature loadings may be due to changes in the insulation occurring at the higher temperatures.

From the foregoing tests, and tests made on stationary models, it was determined that the thermal conductivity of the armature insulation was increased about ten per cent by operation in hydrogen instead of air, while that of the field insulation was practically doubled. These increases in thermal conductivity are practically independent of the hydrogen pressure. The forced heat convection from the internal machine surfaces was estimated to be increased between 30 and 50 per cent by operation in hydrogen at 0.44 pound per square inch pressure instead of in air. For increased hydrogen pressures the forced heat convection varies approximately with the 0.8 power of the absolute hydrogen pressure.

The heating data obtained in these tests indicate that the 6,250-kva generator as originally designed could have its rating at 0.8 power factor increased by very large percentages by operation in hydrogen at various pressures instead of in air, for the same temperatures of the windings. However, these increases in rating would be at the expense of electrical stability, as the short-circuit ratio of a generator is decreased in the same proportion as the output is increased. To obtain the same stability from the hydrogen-cooled generator as from the air-cooled one, the former must be proportioned somewhat differently. For the 6,250-kva generator redesigned for the

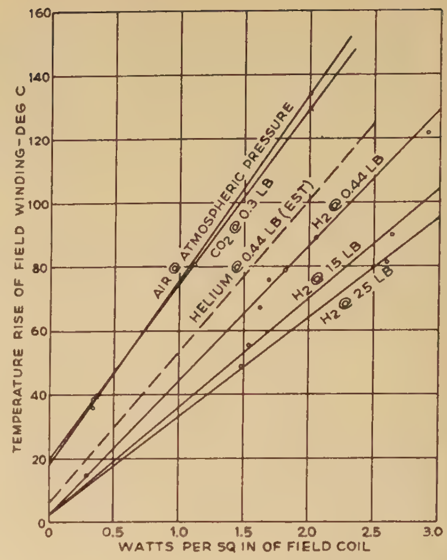


Figure 4. Field heating characteristics of a 6,250-kva generator with respect to temperature of gas leaving coolers, from tests with generator operating in different cooling gases

same short-circuit ratio at all ratings (by maintaining the same stator core dimensions but varying the rotor diameter) the increases in output with hydrogen cooling over the normal air rating, for the same winding temperatures, would be approximately 20, 30, and 35 per cent for hydro-

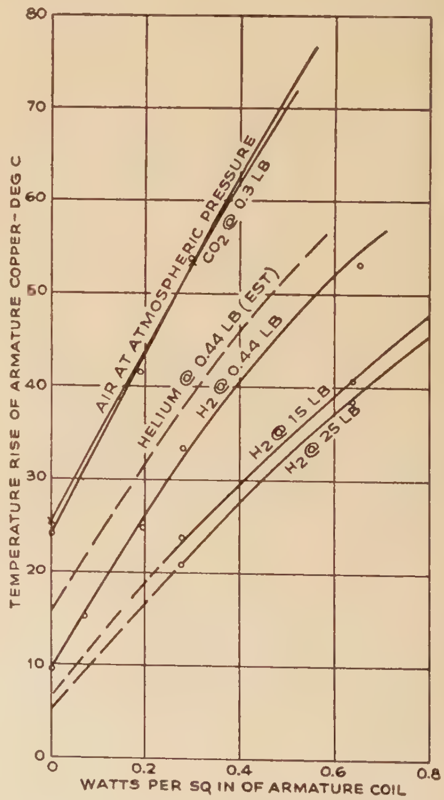


Figure 5. Armature heating characteristics of a 6,250-kva generator with respect to temperature of gas leaving coolers, from tests with generator operating in different cooling gases

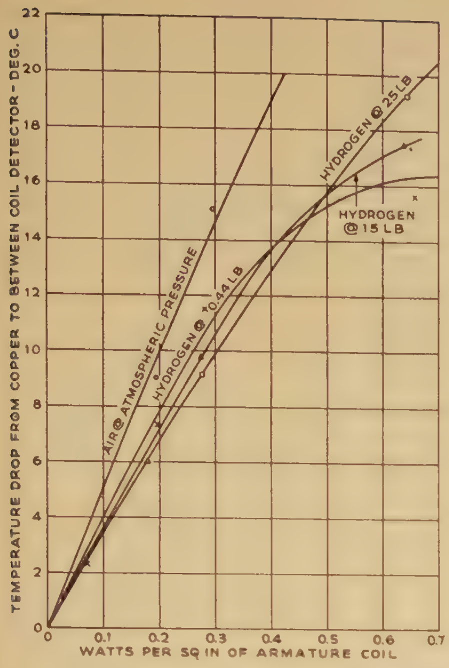


Figure 6. Temperature drop from armature copper to between-coil temperature detector, for different watts per square inch of armature coil, from tests on a 6,250-kva generator operating in air and in hydrogen

gen pressures of 0.44, 15, and 25 pounds per square inch, respectively.

Other Cooling Gases

Tests on the 6,250-kva generator using carbon dioxide as the cooling agent indicated, as shown in figures 4 and 5, that the heating of a machine in this gas is practically the same as with air cooling. Although the density of carbon dioxide is about 50 per cent greater than that of air and its thermal conductivity is about 35 per cent less, these disadvantages are compensated for, with respect to the heating of the windings, by the fact that the forced heat-convection coefficient is about 20 per cent greater in carbon dioxide than in air, and the product of specific heat and density is 39 per cent greater for carbon dioxide than for air, so that 39 per cent more heat can be absorbed by a given volume of the gas for the same temperature rise. Although there is no advantage in the use of carbon dioxide as the cooling agent for generators, as its higher density greatly increases the windage losses, there appears to be a distinct field for its use in the case of induction motors intended for operation in explosive atmospheres. In the past year the General Electric Company has placed in service two induction motors of this type, using carbon dioxide as the cooling agent, the motors being provided with shaft seals similar to those used with hydrogen-cooled generators.

The use of helium as the cooling gas for rotating machinery has been frequently proposed, and has the advantage of effecting a reduction in windage and ventilation losses comparable with that obtained with hydrogen, without the attendant disadvantage of inflammability in mixture with air, possessed by hydrogen. However, as shown by the curves in figures 4 and 5, the cooling effect with helium is distinctly inferior to that obtained with hydrogen, so that the increase in output of a generator by using helium in place of air as the cooling agent would be considerably less than that obtained by the use of hydrogen in place of air.

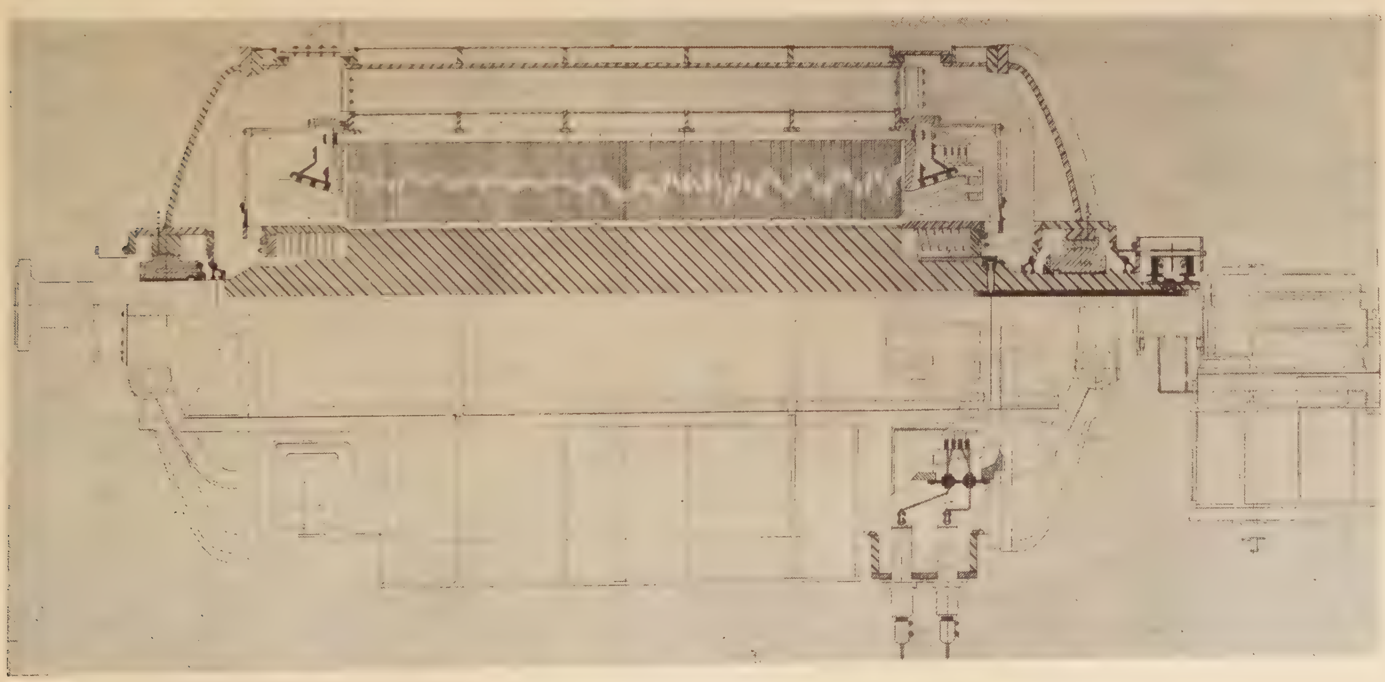
Generator Construction

The type of construction employed with most of the hydrogen-cooled generators built by the General Electric Company is illustrated in figure 7 and includes a cylindrical, gas-tight, outer casing, reinforced with a number of annular supporting-plates. Four gas coolers are usually provided, located within the casing with their long axes parallel to the horizontal axis of the machine. The cooler tubes are made accessible for cleaning without removing the hydrogen from the casing by removing cover plates at either end of the frame. In another design two coolers are used, placed lengthwise of the generator and located in either the top half or the bottom half of the casing.

The outer end-shields of the generator are of either cast-steel or fabricated construction and are usually employed to support the generator bearings, thus minimizing the distance between bearing centers. The joint surfaces between the end-shield halves and between the shields and the casing are carefully machined, and are provided with grooves within the bolting line into which a plastic compound is forced, thereby minimizing the possibility of hydrogen leakage from the joints

The frame construction is designed to withstand safely the explosion pressure of the most explosive mixture of hydrogen and air, with the generator operating at a

Figure 7. Longitudinal cross-section view of a 55,555-kva 3,600-rpm hydrogen-cooled generator



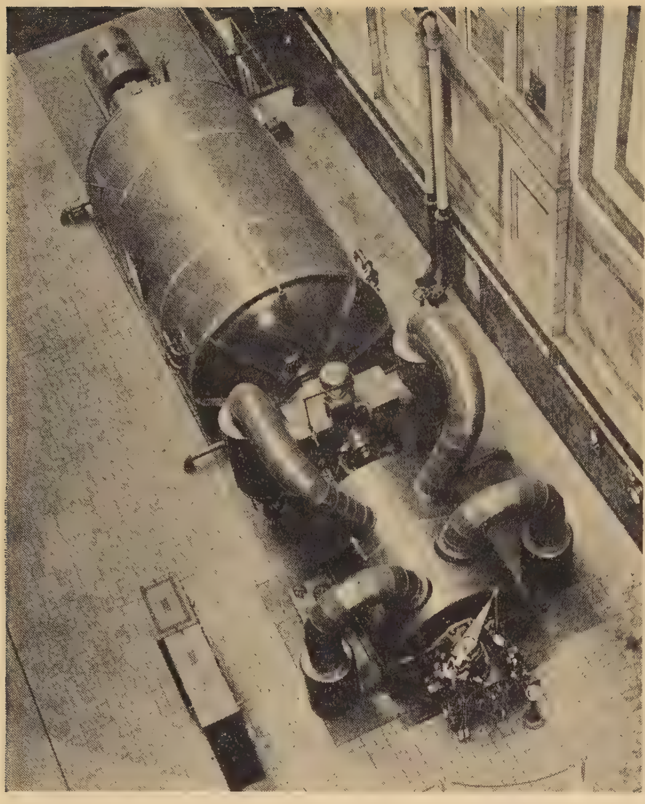


Figure 8. A 53,000-kw 3,600-rpm steam turbine-generator set; generator hydrogen cooled

hydrogen pressure of 15 pounds per square inch. This explosion pressure is estimated to be approximately 100 pounds per square inch.

The rotors of 3,600-rpm hydrogen-cooled generators consist of solid, one-piece steel forgings, having slots milled out of the body portion for carrying the field winding. For many of these generators the field winding is made from aluminum, instead of from copper, which, due to the lower specific weight of aluminum, permits a larger rotor diameter to be employed than with the copper winding and thereby secures a greater rigidity for the rotating shaft. The low rotational loss in hydrogen permits such an increase in rotor diameter, which would not be practical with air cooling.

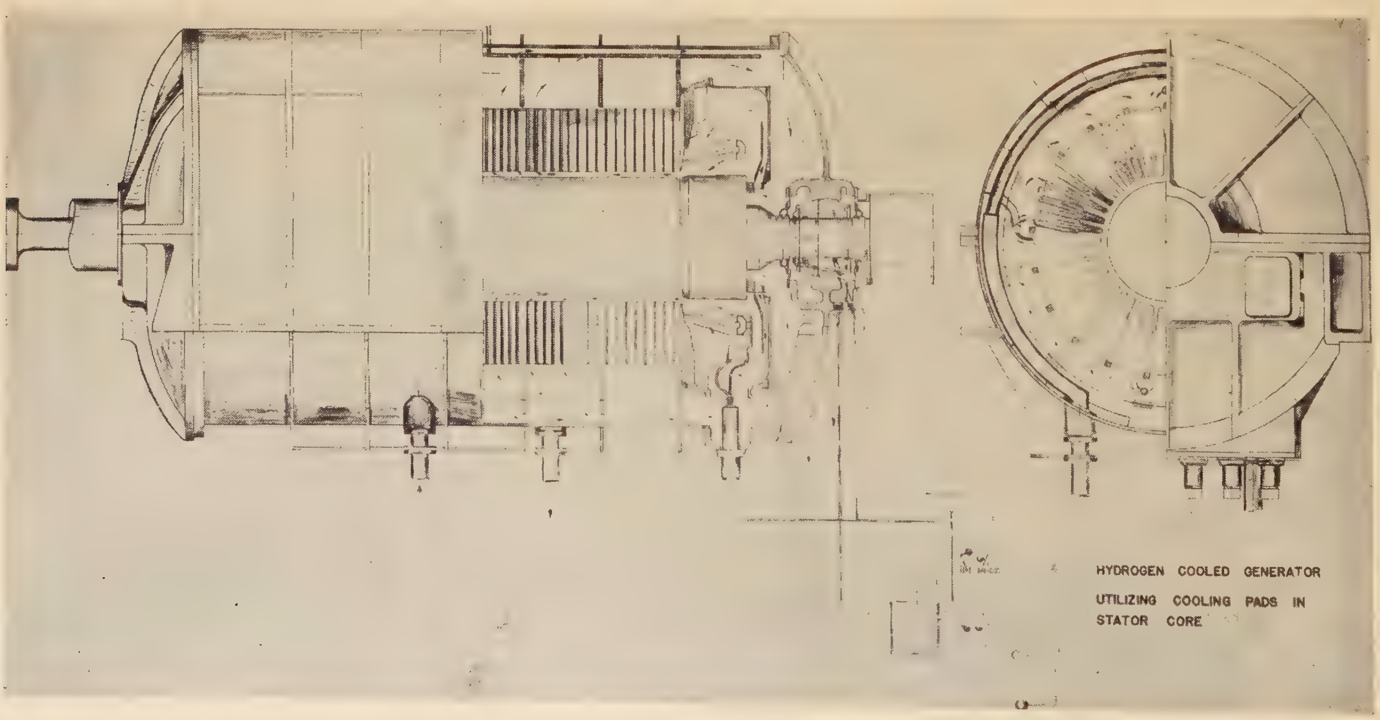
The ventilation of these generators, in all sizes but the very largest, is provided by two centrifugal fans, mounted one on either end of the rotor. For the 176,470-kva 1,800-rpm hydrogen-cooled generator of the Chicago District Electric Generating Corporation, State Line, Ind., ventilation is provided by four motor-driven fans, housed in domes in the top of the casing.

A device is connected to the bottom of the generator casing which operates an alarm if water or oil should start to collect, as could result from a defective cooler-tube or from improperly-functioning shaft seals.

Figure 8 shows a 58,889-kva 3,600-rpm General Electric hydrogen-cooled generator, installed in the Waterside station of the Consolidated Edison Company of New York. This machine has four gas coolers, located two above and two below the floor line. Distilled water is circulated through the coolers, and a heat exchanger external to the machine, supplied with raw water, is used to cool the distilled water.

The 50,000-kva 3,600-rpm hydrogen-cooled generator of the Appalachian Power Company at Logan, W. Va., employs a novel cooling system in which the stator core is cooled by direct contact of the laminations with a number of hollow metal pads, located between the lamination packages, through which distilled water is circulated.[8] The construction of this machine is illustrated in figure 9. The rotor, and the armature end-windings are cooled by the circulation of hy-

Figure 9. Longitudinal and end cross-section views of a 50,000-kva 3,600-rpm hydrogen-cooled generator having water-filled cooling pads in the stator core



drogen over them, the heated hydrogen being cooled at the center of the machine in passing to the back of the core through ducts formed between special finned pads and the laminations. A heat exchanger external to the generator is used to cool the distilled water circulated through the pads. While no other generators of the pad-cooled type have since been built, this cooling arrangement is believed to have several advantages which may sometime encourage its more general use. The use of cooling pads in place of the customary gas coolers permits a more compact construction and reduces the volume of gas that needs to be circulated.

Operating Hydrogen Pressure

The hydrogen-cooled generators built by the General Electric Company are designed to operate normally at a hydrogen pressure of approximately one-half pound per square inch. Several machines have been built, however, with provision for operating at hydrogen pressures up to 15 pounds per square inch, if such operation should become desirable for securing additional kilovolt-ampere output or lower generator temperatures under abnormal water-temperature conditions. Operation at hydrogen pressures greater than about 1.5 pounds per square inch requires the provision of additional control features in the seal-oil and gas control systems.

Shaft Sealing System—Characteristics

Seals Supplied with Vacuum-Treated Oil

The equations for the shaft sealing system employed with these generators are derived in the appendix. These show that, with vacuum-treated oil supplied to the shaft seals, the degree of hydrogen purity maintained in the generator casing is a function chiefly of the degree of vacuum treatment of the oil and the amount of leakage from the casing. The purity is shown to change exponentially with time, following the initial starting-up of the generator, finally reaching a constant value. The amount of hydrogen continuously required by the generator is shown to equal approximately the casing leakage plus the amount of hydrogen absorbed by the sealing oil.

Figure 10 shows the calculated variation in hydrogen purity with time following the starting-up of the generator, for different degrees of vacuum treatment of the sealing oil, for the 50,000-kva 3,600-rpm Logan generator. A leakage from the casing of 0.27 cubic foot per hour has been assumed, based upon tests. The curves show that several weeks of operation are required for the hydrogen purity in the casing to reach the final value corresponding to the vacuum and leakage also that the final value is independent of the initial hydrogen purity in the casing.

Figure 11 shows the calculated final hydrogen purity in the generator casing for different degrees of vacuum treatment of the sealing oil and different assumed values of the casing leakage, for the Logan generator. A curve showing the estimated yearly cost of the windage and ventilation losses of this machine for different values of hydrogen purity in the casing is also given, which illustrates the economic advantage of operating at a high purity. This curve was calculated for an assumed power cost of 0.3 cent per kilowatt-hour and an operating time of 80 per cent. It can be shown from the curves of figure 11 that for values of vacuum treatment less than about 29 inches, a slight casing leakage may increase the hydrogen purity sufficiently to effect a saving in cost of windage loss comparable with the cost of the hydrogen wasted. In practice, however, it is preferable to maintain a high hydrogen purity by maintaining a high degree of vacuum treatment, rather than by leakage, and to have the casing leakage as small as possible.

A high hydrogen purity is, of course, essential from the standpoint of safety, as well as of economy, of operation, since a mixture of less than 72 per cent hydrogen in air is explosive. In practice it is usual never to allow the hydrogen purity in the generator casing to decrease below 90 per cent.

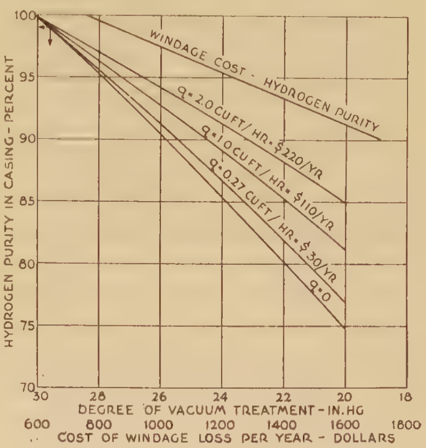


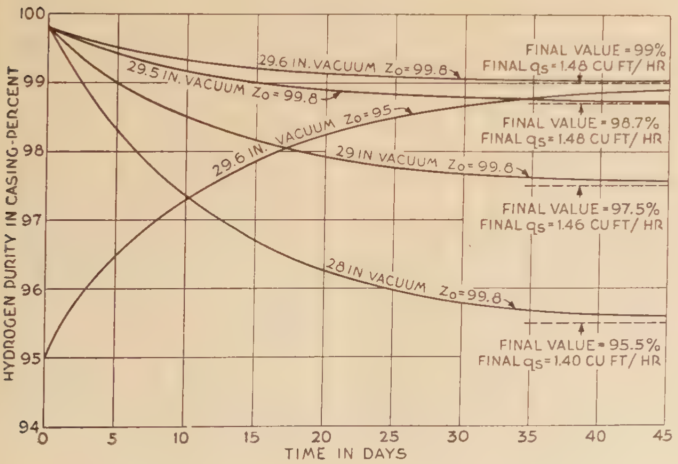
Figure 11. Calculated per cent final hydrogen purity in casing of a hydrogen-cooled generator for different degrees of vacuum-treatment of oil supplied to shaft seals and different rates of hydrogen leakage q. Also estimated yearly cost of windage losses versus per cent hydrogen purity

Hydrogen pressure ten inches water

The degree of vacuum treatment of the sealing oil is determined by the effectiveness of the treating system. For the spray-recirculation system of vacuum treatment used with these generators, the vacuum treatment obtained is generally between 0.1 and 0.3 inch less than the vacuum held in the vacuum tank.

Seals Supplied with Untreated Oil

If the shaft seals are supplied with untreated oil, as may occur under certain emergency conditions of operation, the air given up from the oil flowing to the hydrogen side of the seals will cause the hydrogen purity in the casing gradually to decrease. This will require that the casing be scavenged at intervals with fresh hydrogen to keep the purity always above 90 per cent. Figure 12 shows the calculated and test values of hydrogen purity under this condition of operation, for the Logan 50,000-kva generator.



Barometer 30 inches. Final hydrogen purity by test 99 per cent for 29.7 inches vacuum in vacuum tank. Hydrogen consumption by test 1.48 cubic feet per hour. Hydrogen pressure in casing 10 inches water

Figure 10. Calculated per cent hydrogen purity in casing of a hydrogen-cooled generator versus time for different degrees of vacuum-treatment of oil supplied to shaft seals

The curves show that, for the normal rate of oil flow to the seals, with untreated oil, it is necessary to scavenge the generator casing with fresh hydrogen about once every 15 hours, to maintain the purity between 90 and 95 per cent. The amount of hydrogen of 99.8 per cent purity required to increase the hydrogen purity in the casing from 90 to 95 per cent is, approximately,[7]

$$0.7\times2.3\times1{,}000\log\frac{99.8-90}{99.8-95}=500\text{ cubic feet}$$

where the coefficient 0.7 is an "experience factor" and 1,000 the casing volume. As this amount of hydrogen is required every 15 hours the average hourly hydrogen requirement for this condition of operation would be 500/15=33.3 cubic feet per hour. This compares with 1.48 cubic feet per hour continuously required by this machine to maintain a hydrogen purity of 99 per cent when the vacuum system is in operation. (The amount of hydrogen continuously required to maintain a constant pressure in the casing, when the seals are supplied with untreated oil, is usually negative, that is, gas must be vented from the casing. This follows from the fact that for small values of casing leakage more air is brought into the casing by the sealing oil than hydrogen is discharged by absorption and leakage.)

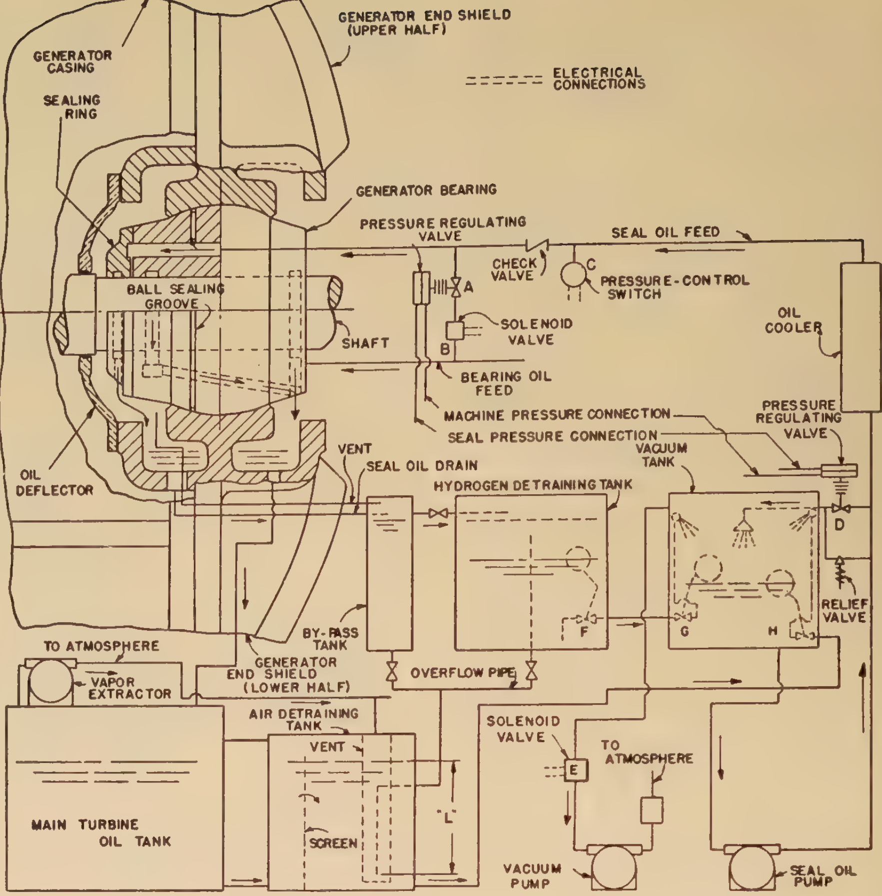


Figure 13. Arrangement of shaft-sealing system for hydrogen-cooled generator, with detail of shaft-sealing arrangement shown for one generator bearing. Arrangement for other bearing is similar

Standstill Operation of Seals

The characteristics of the shaft-sealing system with the generator at rest are somewhat different than with the generator operative, owing to the different values for the gas solubilities in the oil to be used in the seal equations. With vacuum-treated oil supplied to the seals, two different values for both the hydrogen and the air solubilities must be used; for the absorption of gas by the vacuum-treated oil, about the same solubilities may be assumed whether the shaft is rotating or stationary, while for the release of gas by the oil the gas solubilities should be taken as about one-tenth their values for the rotating condition. With untreated oil supplied to the seals, the gas solubilities used in the seal equations should be taken as about one-tenth their values for the rotating condition. The practical results of these differences in seal characteristics for the stationary and rotating conditions are, that with vacuum-treated oil supplied to the seals the hydrogen requirement is only slightly less with the shaft at rest than with the shaft rotating, but the hydrogen purity in the casing is slightly higher. With untreated oil supplied to the seals, however, the amount of hydrogen required with the shaft at rest is about equal to the casing leakage, and the hydrogen purity decreases only about one-tenth as rapidly as with the shaft rotating.

Shaft Sealing System—Arrangement Details

Vacuum-Treating System

The arrangement of the shaft-sealing system employed with General Electric hydrogen-cooled generators is illustrated diagrammatically in figure 13. The sealing ring, which is attached to the generator side of each bearing, contains an annular feed groove to which vacuum-treated lubricating oil is supplied under pressure. The oil passes axially along the shaft in both directions from the feed groove to release grooves in the sealing ring and bearing, into which it is deflected. The oil from the hydrogen-side release grooves passes into the hydrogen-detraining tank, where the larger bubbles of gas absorbed by the oil flowing from the seals are given up and pass back into

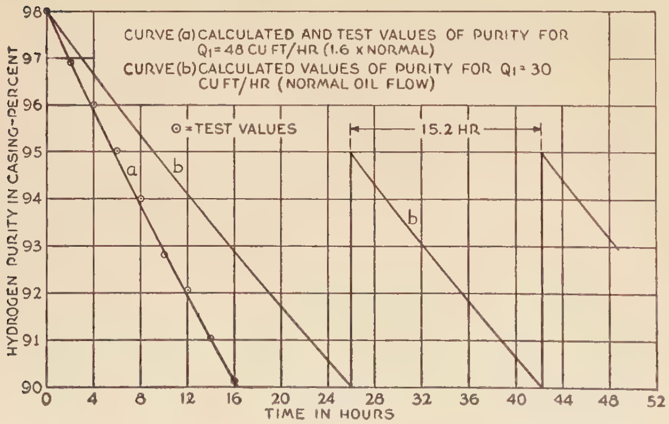


Figure 12. Calculated and test values of per cent hydrogen purity in casing versus time, for a hydrogen-cooled generator operating with untreated oil supplied to shaft seals. Casing scavenged when purity decreases to 90 per cent

Hydrogen pressure 18 inches water

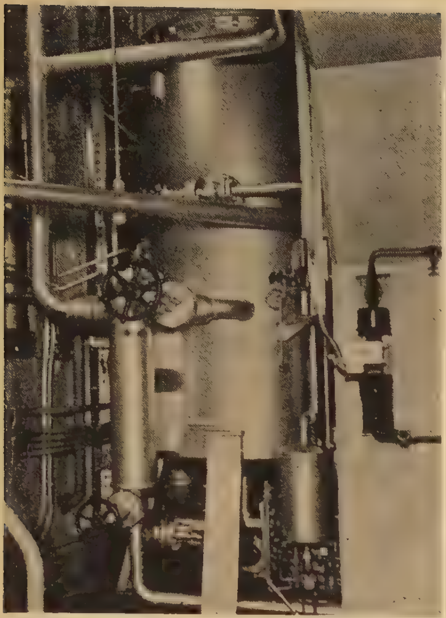


Figure 14. Combination vacuum and hydrogen-detraining tank with auxiliary equipment, for shaft-sealing system of a hydrogen-cooled generator

the generator. The oil from the air-side release grooves unites with the bearing oil and passes to the main oil tank, whence an equal amount flows by gravity to the air-detraining tank (or to an air-detraining compartment in the main oil tank) where the larger bubbles of air contained in the oil are given up. From the hydrogen-detraining and air-detraining tanks the oil passes into the vacuum tank, where practically all of the hydrogen and air remaining in the oil is removed.

Oil is pumped to the seals from the vacuum tank by a rotary pump of the constant-displacement type, having a capacity several times the normal seal oil flow. Pressure regulating valve *D* holds a constant differential between the seal and hydrogen pressures by diverting into the vacuum tank the part of the pump delivery not sent to the seals. The oil diverted through valve *D* enters the vacuum tank through spray nozzles, which serve to expose large areas of the oil to vacuum treatment.

A vacuum of between 0.1 and 0.5 inch of mercury, absolute, is held in the vacuum tank by the operation of a rotary vacuum pump. As the vacuum pump discharges to atmosphere an explosive mixture of hydrogen and air, the pump is made explosion proof.

The by-pass tank shown in figure 13 is used to divert the oil from the seal drain to the air-detraining tank if it becomes necessary to remove the hydrogen-detraining tank from service. Its cross-section area is sufficient to permit partial detraining of the hydrogen from the oil under this emergency condition of operation.

The principal elements of the vacuum-treating system are usually constructed as a unit, as shown in figure 14, and the whole arrangement is conveniently located underneath the generator.

Emergency Seal Oil Supply

In the event of any failure in the vacuum-treating system which would cause failure of the discharge pressure of the seal oil pump, the shaft seals would be supplied with untreated oil from the bearing supply system through pressure-regulating valve *A*, figure 13. This valve is normally open but is prevented from supplying oil to the seals by the normally-closed solenoid-valve *B*. Failure of the discharge pressure of the seal oil pump opens the pressure switch *C*, allowing valve *B* to open. This operation also closes the normally-open solenoid-valve *E* in the suction line of the vacuum pump, preventing the rising of foam in the vacuum tank, which would occur with the spray nozzles unsupplied with oil.

With the shaft seals supplied with oil from the bearing supply system, hydrogen-saturated oil from the seals passes to the air-detraining tank, and thence to the main oil tank, through the overflow pipe in the hydrogen-detraining tank. Operation of the vapor extractor is relied upon to maintain the atmosphere above the oil in the main oil tank well below the lower limit of hydrogen-air inflammability (four per cent) under this condition of operation.

Atmospheric Relief and Scavenging Valves

The maximum operating hydrogen pressure for generators not designed for operation up to 15 pounds per square inch pressure, is represented in figure 13 by the elevation of the oil level in the main oil tank above the low point of the overflow pipe from the hydrogen-detraining tank (dimension *L*). An atmospheric relief valve of the mercury-column type is provided at the hydrogen-detraining tank, figure 15, which discharges hydrogen to atmosphere if the pressure in the casing approaches this limiting pressure. If this valve should fail to operate, hydrogen would be discharged into the vent pipe in the air-detraining tank and would be carried to atmosphere by the vapor extractor.

A solenoid-operated scavenging valve is also provided at the hydrogen-detraining tank, figure 15, operated from the hydrogen control cabinet, which allows hydrogen to be discharged to atmosphere if it becomes necessary to increase the purity of the hydrogen in the casing.

Hydrogen Control

Control System

The system of hydrogen control employed with these generators is illustrated in figure 15. The hydrogen supply is contained in several commercial cylinders, or "bottles," connected with a manifold through pressure-reducing regulators. A solenoid-operated valve controlled by a pressure switch admits hydrogen to the casing from the connected cylinders to maintain the casing pressure within predetermined limits. These are normally from 8 to 12 inches of water.

In filling the casing with hydrogen initially, or in removing the hydrogen from the casing, carbon dioxide is first admitted, through a pipe at the bottom of the casing, and the air or hydrogen discharged from the hydrogen feed pipe. To determine when sufficient carbon dioxide has been admitted to render the mixture nonexplosive with hydrogen or

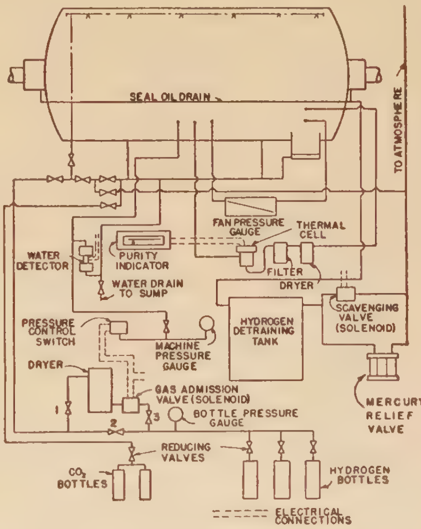


Figure 15. Arrangement of hydrogen piping for hydrogen-cooled generator

air, an Orsat is used, or, in some cases, a special scale on the hydrogen purity indicator is provided.

Purity Indicators

An indication of the percentage hydrogen purity in the generator casing is provided by an instrument operating on the thermal-conductivity principle. Hydrogen from the casing is passed continuously through the analysis cell of the purity-indicating instrument by the action of the generator fans or by continu-

Figure 16. Instrument panel of hydrogen-control cabinet for a hydrogen-cooled generator

Table I. Heating Tests on 31,250-Kva 3,600-RPM Turbine Generator for Dayton Power and Light Company Operating as a Synchronous Condenser at Zero Power Factor Overexcited

All Temperatures in Degrees Centigrade

	Cooling Medium	
	Air	Hydrogen
Kilovolt-amperes at zero power factor	19,200	30,000
Field input, kilowatts	62.5	98
Temperature of gas to coolers	63.4	46.1
Temperature of gas from coolers	40.3	33.1
Temperature rise of gas through coolers	23.1	13.0
Temperature of water to coolers	15.6	18.3
Temperature of water from coolers	26.5	26.5
Temperature rise of water in coolers	10.9	8.2
Water flow to coolers, relative	1.41	1.0
Temperature rise field winding above ingoing gas	67	67
Temperature rise field winding above ingoing water	91.7	81.8
Temperature rise maximum armature temperature coil above ingoing gas	38	32
Temperature rise maximum armature temperature coil above ingoing water	62.7	46.8

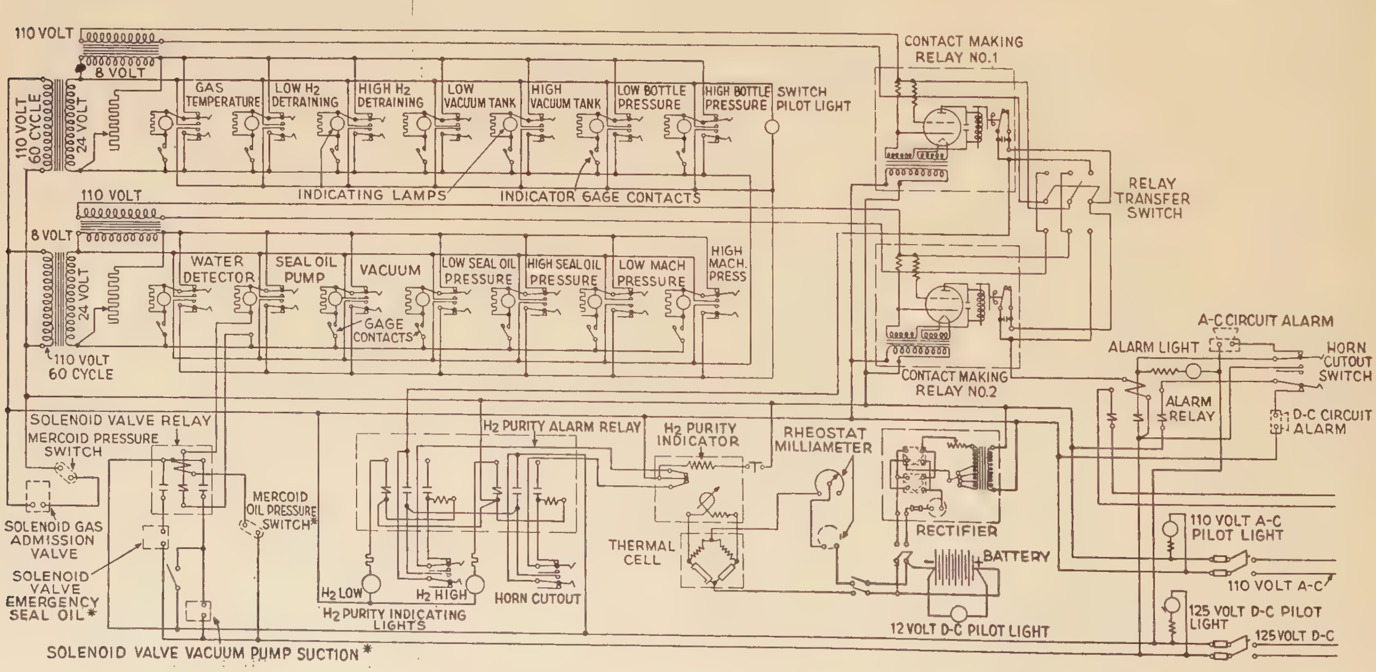
ally wasting a small amount of hydrogen. In the analysis cell a platinum coil, arranged in one of the arms of a Wheatstone Bridge circuit, is passed over by the hydrogen at a slow rate. This coil carries a heating current, supplied by a 12-volt battery, which causes the coil to increase in temperature, and therefore in resistance, by an amount depending upon the thermal conductivity of the gas surrounding it. Since the thermal conductivity of hydrogen is about seven times that of air, a small percentage of air in the hydrogen will cause a relatively large change in the thermal conductivity of the hydrogen and will thus effect a proportionately large change in the coil resistance. The purity indicator is a galvanometer-type of instrument, and indicates the purity of the gas in the analysis cell by comparing the resistance of the above coil with that of a standard coil arranged in another arm of the Wheatstone bridge circuit. A contact in the indicator case operates an alarm to indicate low hydrogen purity.

A secondary indication of the hydrogen purity in the generator casing is provided by the reading of a gauge showing the pressure developed by the generator fans. As the fan pressure, with the generator operating at constant speed, is proportional to the hydrogen density, the scale of this gauge can be calibrated to indicate percentage hydrogen purity.

Control Cabinet

The gas admission device, purity indicating equipment, and the other indicating instruments required for operating the generator in hydrogen are housed in a control cabinet, usually located near the generator on the operating floor. Figure 16 shows the instrument panel of the control cabinet for a 55,555-kva 3,600-rpm hydrogen-cooled generator. The large round instrument shown at the center of the upper row of gauges is the fan-pressure gauge. Directly below it is the hydrogen purity indicator. Other instru-

Figure 17. Schematic diagram of electrical circuits of the control cabinet for a hydrogen-cooled generator. Items with (*) are located away from cabinet



ments shown are the gauge for indicating the hydrogen presssure in the generator casing, the gauge for reading the reduced hydrogen-bottle pressure, a gauge for reading the vacuum in the vacuum tank, and a dial thermometer for indicating the hydrogen temperature at discharge from the coolers. The different instruments are provided with contacts which operate the alarm system of the cabinet to indicate any abnormal condition. The cabinet is mounted on rubber supports to protect the instruments against vibration.

The three hand-valves shown at the bottom of the cabinet in figure 16 correspond with valves 1, 2, and 3 in figure 15.

The alarm system for the control cabinet is represented in figure 17 and includes two contact-making relays of the vacuum-tube type which are used to operate two alarm horns. Operation of the alarm contact of any instrument lights a signal lamp and causes a current to flow through a small step-up transformer; this impresses a grid-bias on the vacuum tube of one of the contact-making relays, causing the relay to drop out and operate the horns. This arrangement permits a minimum passage of current through the instrument contacts for the operation of the horns.

Operating Experience with Eight Hydrogen-Cooled Generators

Within the past 18 months eight General Electric hydrogen-cooled generators in capacities ranging from 31,250 kva at 3,600 rpm to 176,470 kva at 1,800 rpm and with a combined output of 522,164 kva, have been placed in service. The individual ratings of these machines, and their service records, are given in figure 18. These units have operated almost continuously since installation, with no outages from faulty operation of the hydrogen features, and have amply demonstrated the many advantages of hydrogen cooling. The rates of hydrogen consumption have averaged from 35 to 60 cubic feet per day for the six 3,600-rpm units, and are about 65 and 120 cubic feet per day respectively for the two 1,800-rpm units. The costs of these amounts of hydrogen range from $0.45 to $1.50 per day. The hydrogen purities in the casings of these machines have been maintained at values between 97.5 and 99 per cent.

Although some little time is usually required to familiarize the operators with the various details of the auxiliary equipment no real operating difficulties have been encountered, and in most cases the operators have come to regard the operation of hydrogen-cooled generators as being only little more complicated than the operation of the air-cooled type of machine.

Heating Tests on a 31,250-Kva Generator

The first hydrogen-cooled generator to be placed in commercial service, the 31,250-kva 3,600-rpm Dayton machine, was given extensive tests in hydrogen and in air previous to shipment. Some of the test results are shown in table I and figure 19. It will be observed from table I that this machine, operating at zero power factor, carried in hydrogen approximately 56 per cent greater load than in air for the same temperature rise of the field winding, with respect to the temperature of the gas leaving the coolers, while the armature winding operated at a temperature rise even lower. Operating with air as the cooling medium, this generator could carry nearly full load rating with the same heating of the windings as for a standard air-cooled machine. In hydrogen the full-load temperature rises are considerably lower than the normal values for air-cooled machines. The curves of figure 19 show the marked reduction with hydrogen cooling, in the temperature rise of the gas in the air gap—which has an important influence on the heating of the rotor—due to the lower rotational loss in hydrogen.

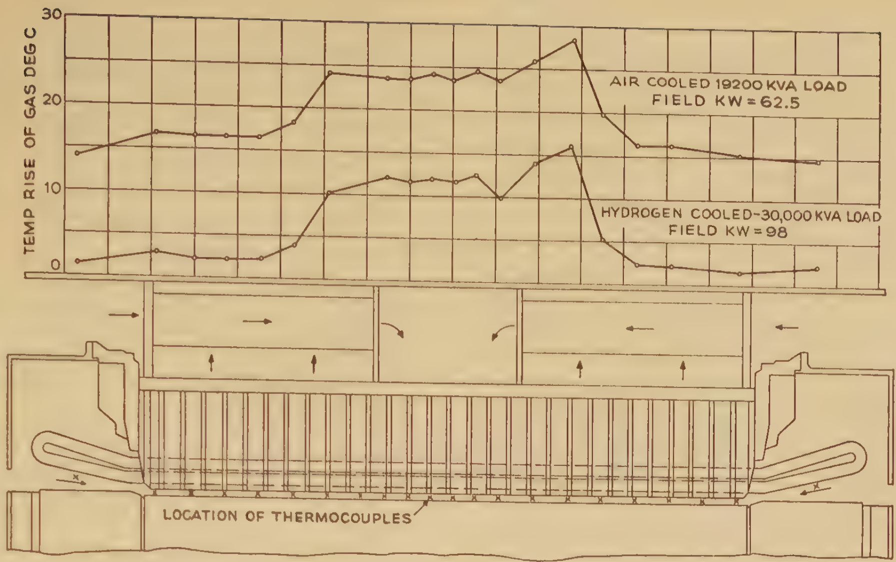


Figure 19. Temperature rise of cooling gas in ventilation circuit of a 31,250-kva 3,600-rpm generator built for operation in hydrogen, from tests in air and in hydrogen, with generator operating as an overexcited synchronous-condenser at zero power factor

Paths of ventilating gas shown by arrows

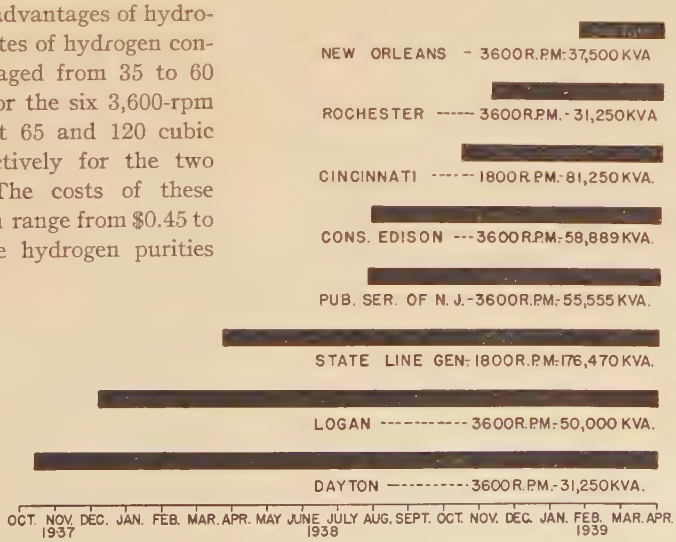


Figure 18. Ratings and lengths of time in service of eight General Electric hydrogen - cooled generators

Future Trends in Generator Design

It will be apparent, from the large number of hydrogen-cooled generators now in successful operation, that this new type of machine has now definitely emerged from the experimental stage and has become an accepted piece of central-station equipment. Much remains to be done, however, now that some operating experience with these machines has been gained, toward simplification of the equipment and improvement of the general design. In developing the design described in the foregoing, the General Electric Company has endeavored to obtain a system that

would be as reliable and as nearly "fool-proof" as possible, even at the expense of some complexity. Present developmental work is being directed toward the reduction in the number and size of the auxiliaries and in the simplification of the control equipment. A new type of shaft seal employing smaller shaft clearances than the present seal has been developed, which permits the use of smaller treating tanks and equipment than are used at present, and requires less hydrogen. A new purity indicator, with hydrogen and carbon dioxide scales, has been developed, which is more rugged than the indicator used on the earlier machines. A new stator frame design permits greater accessibility to the coolers for servicing, than the present design.

At present no hydrogen-cooled generators smaller than 28,125 kva at 3,600 rpm or smaller than 81,250 kva at 1,800 rpm have been built, or are under construction, by the General Electric Company. For sizes appreciably smaller than these, the gains with hydrogen cooling do not at present appear sufficient to justify the additional expense and complication involved in its use. However, further improvements in design, and increasing familiarity with hydrogen cooling on the part of the industry may eventually make desirable the extension of hydrogen cooling to include even the smaller sizes of machines. For the larger sizes, that is, above about 37,500 kva at 3,600 rpm and 75,000 kva at 1,800 rpm, it is probable that practically all future generators will be hydrogen cooled.

Appendix

Equations of the Shaft Sealing System

In the following are derived the equations for the hydrogen consumption and the hydrogen purity in the casing of a hydrogen-cooled generator provided with shaft seals of the oil-film type. These equations are based upon the theory of this type of shaft seal as given in the article of reference 5.

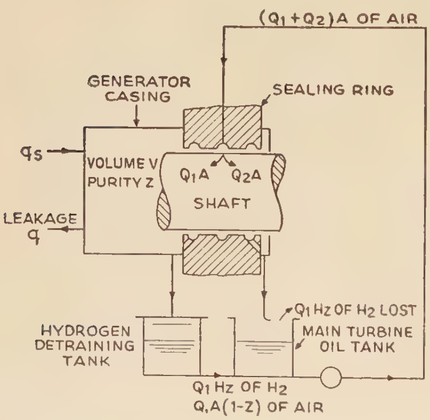


Figure 20. Schematic diagram of shaft-sealing system for hydrogen-cooled generators, using untreated oil

(a) Seals Supplied With Vacuum-Treated Oil

Referring to the schematic diagram of the sealing system in figure 2, let

Q_1 = number of cubic feet of oil flowing into the generator casing per hour (from both shaft seals)

Q_2 = number of cubic feet of oil flowing out on the air side per hour (from both shaft seals)

x = number of cubic feet of hydrogen contained in one cubic foot of oil coming from the vacuum tank at the time t

y = number of cubic feet of air contained in one cubic foot of oil coming from the vacuum tank at the time t

q = number of cubic feet of gas leaving the casing per hour as leakage at the time t

q_s = number of cubic feet of hydrogen of purity S entering the casing per hour at the time t

t = time in hours

H = solubility of hydrogen in the oil leaving the seal (that is, the number of cubic feet of hydrogen in one cubic foot of oil)

A = solubility of air in the oil leaving the seal (that is, the number of cubic feet of air in one cubic foot of oil)

z = per unit hydrogen purity in casing at the time t

$1-z$ = proportion of air in casing at time t

Z_0 = per unit initial hydrogen purity in drum (that is, $z=Z_0$ at $t=0$)

V = total volume of gas in drum and connected apparatus in cubic feet

S = proportion of hydrogen in gas supply per unit

$1-S$ = proportion of air in gas supply, per unit

P = absolute pressure corresponding to degree of vacuum treatment of oil, atmospheres

For the determination of the hydrogen consumption, referring to figure 2, note that the amount of gas in the oil flowing to the seals equals the difference between the amount of gas in the oil entering the vacuum tank and the amount of gas discharged from the vacuum pump. This can be shown to be

$$Q_1P[Hz+A(1-z)]+Q_2AP$$

which must equal

$$Q_1(x+y)+Q_2(x+y)$$

Equating the hydrogen terms and the air terms in these two expressions gives

$$x=Q_1\frac{PHz}{Q_1+Q_2} \tag{1}$$

and

$$y=\frac{Q_1PA(1-z)}{Q_1+Q_2}+\frac{Q_2AP}{Q_1+Q_2} \tag{2}$$

For the condition of constant gas pressure in the generator casing the following equation must be true

$$Q_1(x+y)+q_s=q+Q_1Hz+Q_1A(1-z) \tag{3}$$

Substituting the values of x and y from equations 1 and 2 in (3) and solving for q_s gives

$$q_s=q+Q_1[Hz+A(1-z)]-\frac{PQ_1}{Q_1+Q_2}\{Q_1[Hz+A(1-z)]+Q_2A\} \tag{4}$$

cubic feet per hour

for the amount of hydrogen that must be continuously supplied to the generator casing to make up for that lost through absorption in the sealing oil and that lost by leakage. For high degrees of vacuum and purity both P and $(1-z)$ are small so that the terms of equation 4 containing these quantities may be neglected and the equation for the approximate hydrogen requirement of the generator written as

$$q_s=q+Q_1Hz \text{ cubic feet per hour} \tag{5}$$

To determine the degree of hydrogen purity z that would be maintained in the generator casing with the system shown in figure 2, let the purity at time t be z, and at time $t+dt$ be $z+dz$. The latter purity can be shown to be

$$z+dz=\frac{Vz-[Q_1(Hz-x)+qz-q_sS]dt}{V} \tag{6}$$

Substituting the value of x from equation 1 an expression for dz/dt is obtained of the form

$$\frac{dz}{dt}=\frac{-z}{V}C+D \tag{7}$$

the solution of which is

$$z=\frac{DV}{C}+\left(Z_0-\frac{DV}{C}\right)\epsilon^{-\frac{Ct}{V}} \tag{8}$$

where

$$C=q+\frac{Q_1}{Q_1+Q_2}[Q_1(1-P)+Q_2]\times[H-S(H-A)] \tag{9}$$

and

$$D=\frac{S}{V}[q+Q_1A(1-P)] \tag{10}$$

The second term in equation 8 becomes zero for t = infinity, so that the first term represents the final hydrogen purity in the casing. In figure 10 the hydrogen purity in the casing of the Logan generator, as a function of time following the starting-up of the generator, has been calculated from equation 8 for different values of P, for the value of q obtained in tests on this machine. In figure 11 the final values of purity from equation 8 have been calculated for different values of P and q. In these calculations S has been taken as 0.998. The rates of oil flow from the gas and air sides of the seal have been taken from tests as $Q_1=30$ and $Q_2=61.6$ cubic feet per hour, respectively. An average temperature of the seal oil of 42 degrees centigrade was used, for which the hydrogen and air solubilities were taken as $A=0.11$ and $H=0.041$, respectively. The casing volume V was taken as 1,000 cubic feet.

(b) Shaft Seals Supplied With Untreated Lubricating Oil

For this condition of operation figure 20 applies. For the condition of constant gas pressure in the generator casing we have, using the symbols given under (*a*),

$$q_s+Q_1A=Q_1Hz+Q_1A(1-z) \quad (11)$$

whence

$$q_s=q-Q_1z(A-H) \text{ cubic feet per hour} \quad (12)$$

for the amount of hydrogen continuously required by the generator with the seals supplied with untreated lubricating oil. For small values of q, q_s is negative, that is, hydrogen must be discharged from the casing to hold a constant pressure.

To determine the hydrogen purity in the generator casing under this condition, referring to figure 20 the purity at any time $t+dt$ can be represented by the equation

$$z+dz=\frac{Vz-(Q_1Hz+qz-q_sS)dt}{V} \quad (13)$$

whence

$$\frac{dz}{dt}=\frac{-ZE}{V}+F \quad (14)$$

The solution of equation 14 is

$$z=\frac{F}{E}V+\left(Z_0-\frac{FV}{E}\right)\epsilon^{-\frac{Et}{V}} \quad (15)$$

where

$$E=q+Q_1[H+S(A-H)] \quad (16)$$

and

$$F=q\frac{S}{V} \quad (17)$$

In figure 12 the hydrogen purity in the casing of the Logan generator, with untreated oil supplied to the shaft seals, has been calculated from equation 15 for two different values of oil flow to the hydrogen side of the seals, namely, $Q_1=30$ and $Q_1=48$ cubic feet per hour. For $Q_1=48$ cubic feet per hour, using an air solubility $A=0.11$ in equation 15 gave values of purity z which checked the test values of purity exactly. This value of A was used, therefore, in calculating curve *b* in figure 12 and the curves of figure 10.

Solubilities of Air and Hydrogen in the Sealing Oil

In applying the equations of the foregoing section, the solubilities of air and hydrogen in the oil supplied to the shaft seals must be either known or assumed. The curves in figure 21 give the solubilities of air and hydrogen in transformer oil, which has a viscosity considerably lower than that of turbine oil and should therefore absorb gas more readily. Tests made by the writer indicated the solubility of air in turbine oil to be 10.8 per cent at 40 degrees centigrade, which agrees closely with the curve for transformer oil in figure 21.

In the calculation of figure 12 in the preceding section the assumption of an air solubility of 11 per cent, for oil at 42 degrees centigrade, was found to give transient values of hydrogen purity in the casing of the Logan generator which checked the

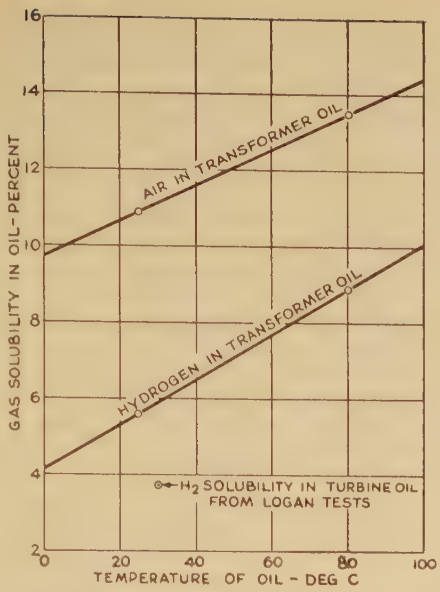


Figure 21. Solubilities of air and hydrogen in transformer oil at atmospheric pressure and at the temperature of the determination, for different oil temperatures, from tests by Rodman and Maude[9]

test values exactly. This value for air solubility also agrees closely with the curve for transformer oil given in figure 21. However, calculation of transient values of hydrogen purity for the Cincinnati generator indicated that an assumption of an air solubility of seven per cent, for oil at 36 degrees centigrade, was required in order to check the test values of hydrogen purity. However, the turbine oil for the Cincinnati machine had a viscosity of 200 seconds Saybolt Universal at 36 degrees centigrade, as compared with a viscosity of 130 seconds Saybolt Universal at 42 degrees centigrade for the oil in the Logan turbine. Also the shaft speed of the Logan generator was 45 per cent higher than that for the Cincinnati generator, so that there was greater likelihood that all the air in the seal oil of the Logan machine would be given up to the hydrogen in the casing than would be the case for the Cincinnati generator.

It may be deduced from the above that, for the solubility of air in the turbine oil to be used in the equations for the shaft seal, the curve for air solubility in transformer oil in figure 21 may be assumed correct if the oil is of low viscosity, and if the shaft speed is of the order of 12,000 feet per minute; however, for oils of high viscosity and at fairly low shaft speeds, the air solubility should be taken as 60–70 per cent of the values for transformer oil.

For determining the solubility of hydrogen in the turbine oil, tests made on the Logan generator at standstill with the shaft seals supplied with treated and with untreated oil were used. Substituting the test values of hydrogen consumption for these two conditions in equations 4 and 11 of the preceding section gave a value for hydrogen solubility of 0.037 at 30 degrees centigrade. This is 62 per cent of the solubility of hydrogen in transformer oil at this temperature. Assuming this same percentage to apply for other temperatures, the hydrogen solubility at the running temperature of 42 degrees centigrade was estimated to be 0.041 and this value was used in estimating the curves in figures 10 and 11.

Until more definite information is available regarding the solubility of hydrogen in turbine oil under the conditions which obtain at the shaft seals of a hydrogen-cooled generator, it may be considered sufficiently accurate to assume this solubility to be from 60 to 70 per cent of the solubility for hydrogen in transformer oil, as given by figure 21.

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Discussion

Sterling Beckwith: See discussion, page 34.

E. H. Freiburghouse (General Electric Company, Schenectady, N. Y.): The reliability of hydrogen cooling of large turbine generators has been thoroughly demonstrated. Referring to figure 18 of Mr. Snell's paper, it is seen that a continuous service record without interruption from any cause associated with the hydrogen-cooling features has been obtained on all of the generators of the design described in his paper. Nine of these machines are now in service. As a result of our operating experience with these machines, however, a number of simplifications and improvements have been found possible and these are being incorporated in the designs of our newer hydrogen-cooled generators. Some of these design changes and novel construction features will be mentioned in this discussion.

Figure 1 of this discussion shows the type of construction used with our latest hydrogen-cooled generators of the 3,600-rpm type, and the arrangement of the gas-

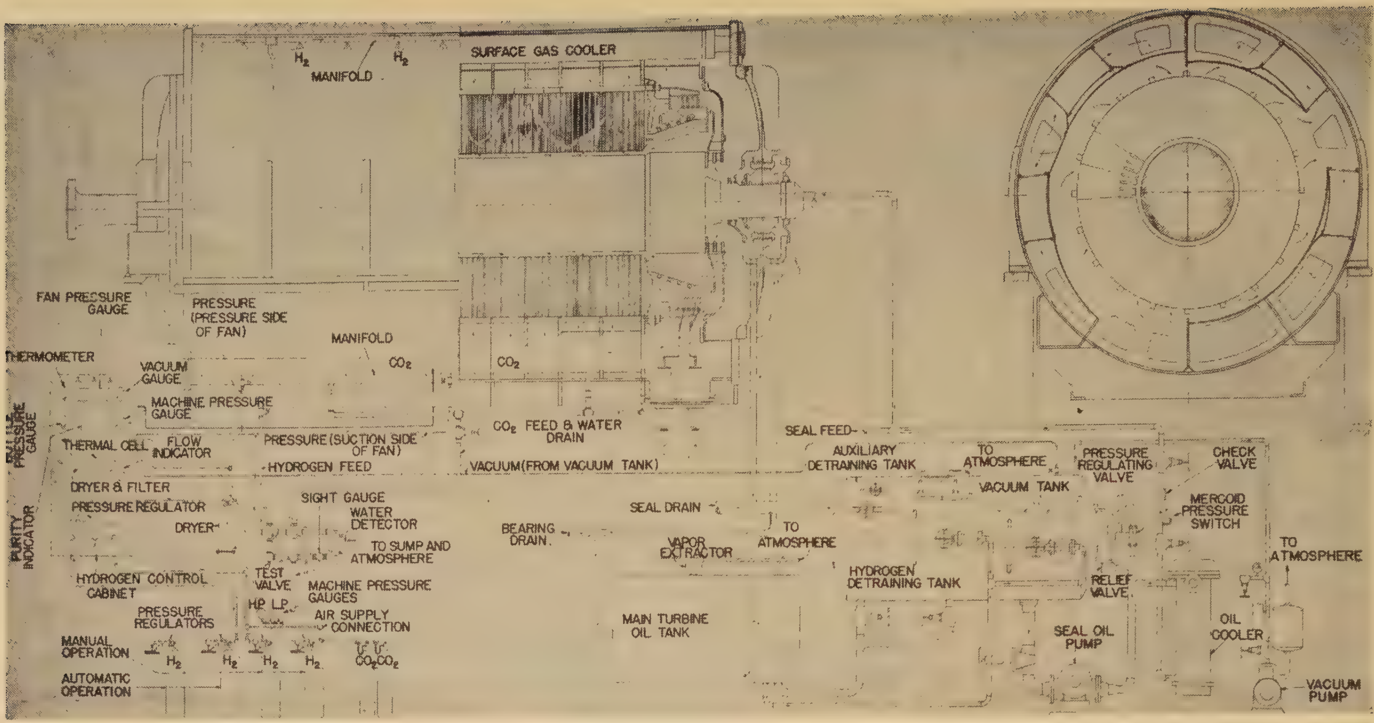


Figure 1

control and shaft-sealing systems. In this design the four gas coolers are located above the floor line, with the water connections at the extreme ends of the frame instead of at the sides, as in the earlier design. This construction permits easier cleaning of the cooler tubes than with the former arrangement.

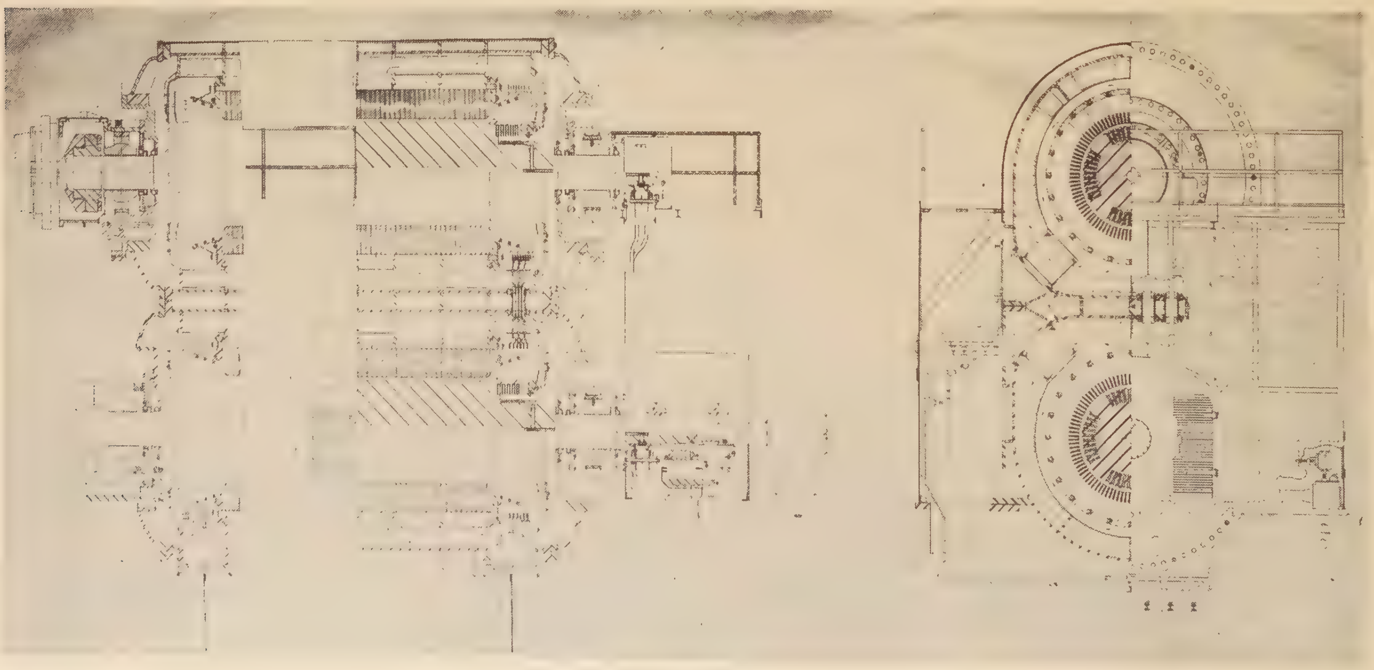
The arrangement of the gas control system shown in the above figure is appreciably simpler than the arrangement formerly used. Wherever possible, valves with diaphragm-packed stems are being used to reduce the possibilities of leakage. The solenoid gas-admission and scavenging valves, used with our present machines, have been replaced in the arrangement shown in figure 1 with diaphragm-type valves. This was done to avoid the leakage experienced with the solenoid valves, and also to eliminate the mercury relief valve.

The arrangement of the carbon-dioxide equipment shown in figure 1 is similar to that used with the machines now in service, and includes heating equipment which permits the carbon dioxide to be admitted to the generator casing as a gas. Carbon dioxide in the liquid form may be used thereby reducing the time for purging and eliminating the heating equipment, however, somewhat more carbon dioxide would be required.

Our laboratory has developed a new type of hydrogen purity indicator for use with hydrogen-cooled machines, which is more rugged and also more accurate than the indicator now used. This operates on the thermal-conductivity principle, as does the present indicator, but uses alternating instead of direct current, thus eliminating the need for the storage battery and rectifier.

The horizontal arrangement of shaft-sealing equipment shown in figure 1 is being used with a number of generators now under construction. This provides greater accessibility of the parts; however, a vertical arrangement of the treating tanks has been used wherever it was more suited to the station space. The different elements of either arrangement may be mounted on a common base and assembled as a unit.

Figure 2



One of the more unusual designs for hydrogen-cooled generators is that employed with the 137,500-kva vertical compound turbine generator set built for the Ford Motor Company, which is illustrated in figure 2 of this discussion. This generating unit, which is now being installed at Dearborn, Mich., consists of two separate hydrogen-cooled generators, each of 68,750 kva at 1,800 rpm, which are mounted one on top of the other. Each generator is provided with a double armature winding, and the windings of the two machines are paralleled through connections at one end as shown in the above figure. The casing of one generator is connected with the casing of the other through the conduits used for the electrical connections between the two armatures, so that the two casings are considered as one in filling or emptying the casings with hydrogen and carbon dioxide. However, each machine is provided with its own hydrogen purity indicator and a separate fan pressure gauge. Two gas coolers are provided with each generator, those of the upper generator being located in the bottom of the frame, while those of the lower generator are in the upper part of the frame. The hydrogen control panel, item 11, figure 2, is located in the side of the frame structure of the lower generator. A single set of treating tanks is provided for the shaft-sealing oil for both generators, also a single seal oil pump and vacuum pump.

This paper clearly indicates that much has been accomplished and important progress is being made in regard to the cooling of turbine generators by means of hydrogen. Operating experience is being rapidly accumulated, also further improvements in design and materials may be expected. It is, therefore, certain that hydrogen cooling will be an essential feature of large high-speed machines which are to be built, and generators of even larger power output per shaft will be possible in the near future.

Carl J. Fechheimer (consulting engineer, Milwaukee, Wis.): The desirability of using hydrogen as a cooling medium in large high-speed electrical machinery has been recognized since the presentation of the splendid paper by Knowlton, Rice, and Freiburghouse in 1925. Having done considerable work some years ago in the development of gland seals, devices for control and proportioning of parts when hydrogen cooling was beginning to be discussed, the paper by Mr. Snell is of especial interest to me.

It seems to me that the fear of an explosion has caused our engineers to be overly cautious. If an inert gas is used properly as an intermediary when changing from air to hydrogen or the reverse, it should not be necessary to burden the generator with the additional expense attended with making it explosion proof. Particularly with the large diameters associated with the large slower speed 1,800-rpm machines, it is essential to make the enclosing brackets with thick walls, probably with ribbing, and to curve them, so that they will withstand an explosion safely. I would inquire of the author whether consideration has been given to the design which will be sufficiently strong for ordinary operation only, and if so, by what percentage the cost of a large 1,800-rpm generator would thereby be reduced? Also, if the cost would thereby be reduced appreciably, and if the control equipment and shaft seals were simplified, as suggested by Mr. Snell, would it not be economically desirable to build hydrogen-cooled turbine generators for smaller ratings than recommended in the paper?

It is of interest to study table I on temperatures. The losses with air for 64 per cent of the load with hydrogen are 78 per cent higher as given by the gas temperature rise, and 87 per cent higher as given by the water temperature rise. The fairly close check between the two methods of computation is interesting. Undoubtedly, the windage loss was a very large percentage of the total loss. Even with considerably higher I^2R losses, the field temperature rise above the ingoing gas temperature was the same, but was ten degrees less with hydrogen, if referred to the ingoing water temperature. As it is the ingoing water that is the ambient, why not take the water temperature, and not the gas temperature, as reference?

The armature-coil temperature rises are even more favorable for hydrogen, they being only 75 per cent as high (referred to the ambient water), even though the I^2R loss was approximately 2.4 times as great. This considerable gain was undoubtedly due chiefly to the relatively high heat conductivity with hydrogen, which reduced the thermal drop from the copper to the iron, the transverse drop in the iron packages, and the heat transfer drop from the cooling surfaces to the cooling medium. Has Mr. Snell given consideration in the design to the feasibility of using thicker iron packages, and of increasing the current density in the armature copper, than would be employed in an air-cooled machine?

It seems from the test results that the usual ratio of rating for hydrogen to air cooling of 1.2 to 1.3 is entirely too conservative. If the data for this machine are typical of other hydrogen-cooled turbine generators, even 50 per cent increase in rating is conservative.

In figure 9 the use of diffusers to improve the efficiency and increase the pressure of the centrifugal fan is interesting, and was considered many years ago. It was found that propeller fans were more efficient, were not so much restricted at entrance as centrifugal fans, and could be applied to larger sizes of machines. It is worthy of note that with the very high peripheral velocities of the centrifugal fans, more pressure can be developed than is necessary; the result is that the fans are not operated at the most favorable point on their pressure-volume curves. Is it not likely, as shown in table I, that the high gas temperature rise when air is used, is largely due to the high fan pressure and rather low fan efficiency? If so, perhaps the ratio of ratings would not be so high (as suggested in the preceding paragraph) if the temperature rise of the air when passing through the fans were reduced?

As indicated in figure 9, a number of hollow metal pads between lamination packages, were used for the water coolers. The details of construction are not entirely clear and I would inquire whether the pads interfered with the flow of hydrogen, and whether the thermal drops from laminations to water were appreciably altered, as compared with the usual finned surface cooler.

Perhaps one thing that has helped to bring the construction of hydrogen-cooled machines to the forefront, is that now we can calculate quite closely the fans, pressures and volumes, as well as the distribution of the cooling medium throughout the machine, which could not have been done a comparatively few years ago.

It seems that today, instead of hydrogen-cooled machines being hazardous, they are actually the safest machines, because there is no internal gas to support combustion, there is negligible damage from corona, and they are as clean after years of service as when first placed in operation.

P. L. Alger (General Electric Company, Schenectady, N. Y.): When hydrogen cooling for electrical machinery was first proposed, the chief objection to its use was the fear of an explosion. Tests made to determine the pressure developed in an explosion of the most explosive hydrogen-air mixture, initially at atmospheric pressure, indicated that the explosion pressure, for a machine assembled with core and windings, would not exceed 50 pounds per square inch. The theoretical explosion pressure, for no heat loss to the surroundings, is 180 pounds. Since, however it is not difficult to construct the frame of the machine to withstand a force of 200 pounds per square inch, it is apparent that there is very little to fear from an explosion in a hydrogen-cooled machine.

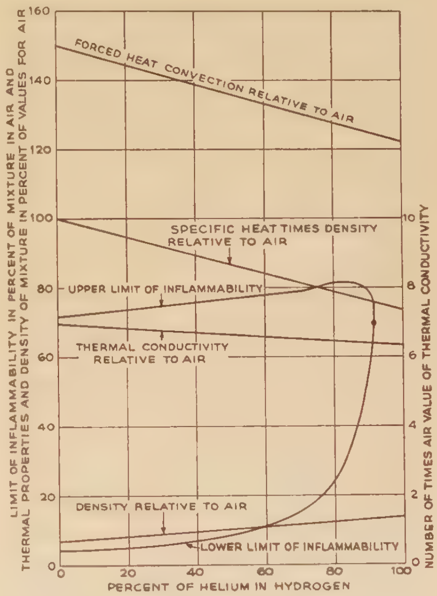


Figure 3

Nevertheless, it is interesting to consider other gases which could be used for cooling that are not subject to these explosion risks, slight as they are, thus promoting economy in methods of installation and handling. An obvious possibility is the use of helium. The light weight of helium gives very low windage losses, but its materially higher cost and its inferior cooling properties make it undesirable for use as a pure gas. It therefore occurred to me that the properties of a mixture of helium and hydrogen should be investigated, in the hope of obtaining a gas free from explosion risk, that would pre-

serve practically all of the advantages of pure hydrogen. The results of a theoretical study of this subject by Doctor Saul Dushman and D. S. Snell are presented in the two accompanying figures.

Figure 3 of this discussion shows the limits of inflammability of a mixture of hydrogen and helium, also the thermal properties of

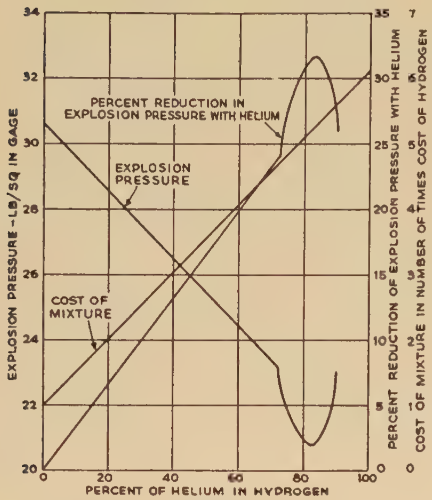


Figure 4

the mixture compared with air. Figure 4 shows the calculated effect on the explosion pressure at the upper limit of inflammability, of mixing helium with hydrogen. The curves were calculated for an assumed heat loss of 25 per cent. The amount of helium shown to be required, and its cost, in order to produce a significant reduction in the explosion pressure, are so large, however, as to make this procedure unattractive.

C. F. Hill and L. J. Berberich (Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): The operating experience described in these papers on hydrogen-cooled generators indicates that hydrogen will in the near future be the generally accepted cooling medium for machines of the larger ratings. It should be mentioned again that electrical insulation is subjected to fewer deteriorating influences when operating in hydrogen as compared with air.

We should like to re-emphasize one or two of these. The effects of oxygen, ozone, and oxides of nitrogen, the last two being produced only under corona conditions, are completely absent. These phenomena have been discussed in previous papers and need be only mentioned here. But even more important, is the problem of moisture absorption by the insulation which can be almost completely eliminated in the hydrogen-cooled machine.

Here the only source of moisture is from the oil supplied to the hydrogen seals. The moisture is, of course, introduced into the lubricating oil system by the turbine. When moisture-laden oil is passed into the seals, which run in the neighborhood of 100 degrees centigrade, a considerable amount of water is vaporized into the machine. This water vapor acts as a contaminant to the hydrogen and increases the apparent hydrogen consumption. Mr. Snell in his paper stresses the contaminating influence of air from the seal oil, but it is our experience that moisture can also be a serious diluent of the hydrogen.

This moisture problem has been eliminated by the combination of an oil vacuum treating unit and a gas drying unit which are described by Messrs. Ross and Sterrett. The simple vacuum-treating unit reduces the water content of the oil to less than 0.003 per cent by weight. With added complications, the vacuum system could be made to reduce the moisture content still lower. But even at very low concentrations, some moisture is always vaporized from the oil in passing over the seals which will gradually build up moisture concentration in the machine and this will eventually increase the hydrogen consumption. This, together with the possibility of failure of the oil vacuum treating system, justifies the addition of the exceedingly simple activated-alumina gas dryer described by Messrs. Ross and Sterrett.

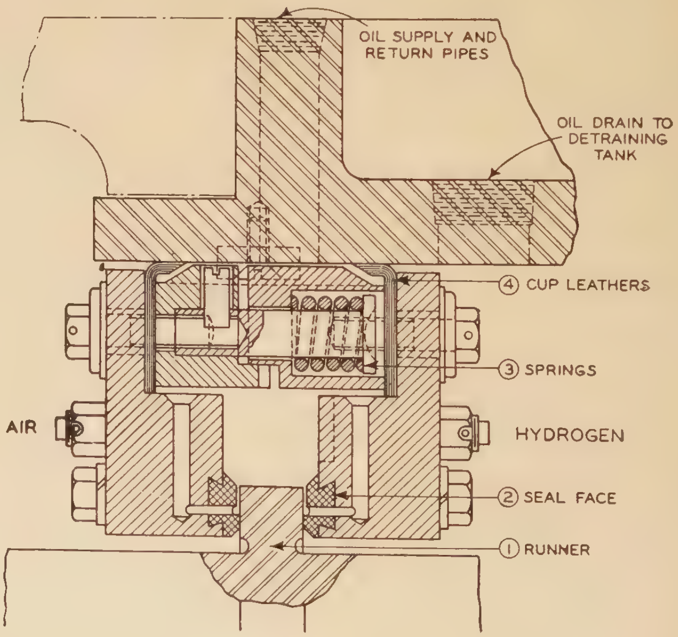
We have studied one of these machines and the results may be of interest. Actual determination of the moisture content of the gas in a 50,000-kw machine which had been in operation for some time has been made. With the vacuum-treating unit and dryer in operation the moisture content was approximately 0.01 gram per cubic foot of gas. This corresponds to a relative humidity of 0.4 per cent at machine temperature of 55 degrees centigrade (machine was only partially loaded at time of test), a dew point in the neighborhood of −25 degrees centigrade, and volume concentration of water vapor of approximately 0.06 per cent. The effectiveness of this system of moisture and air removal is attested by the fact that the hydrogen consumption for this machine is only 20 cubic feet per day. A similar test was made on the same machine with the moisture elimination system not in operation and a water content of roughly 1.0 gram per cubic foot gas was found. This corresponds to a relative humidity approximately 25 per cent at 55 degrees centigrade, a dew point of 30 degrees centigrade and volume concentration of water vapor of 4.8 per cent. Under these conditions the hydrogen consumption was very high and water was condensed from the gas at the coolers which were operating approximately 10 degrees centigrade below the dew point. The necessity of removing moisture from the oil going to the seals is thus indicated.

Returning again to the electrical insulation, the combined oil-treating and gas-drying system so effectively removes moisture and air from the oil that the insulation may be considered almost hermetically sealed in an inert medium. The problems caused by the effects of ozone, oxides of nitrogen, moisture, and accumulation of dirt are all eliminated. The performance of the insulation in hydrogen should therefore be far better than in air.

S. H. Mortensen (Allis-Chalmers Manufacturing Company, Milwaukee, Wis.): The authors of the papers on hydrogen-cooled turbine generators have so admirably covered the design and operating problems incidental to hydrogen-cooling of turbine generators, that I find nothing to add except a description of the Allis-Chalmers company's hydrogen-shaft seal and a discussion of its effect upon certain faces of the generator operation.

The Allis-Chalmers company's shaft seal is shown in figure 5 of this discussion and consists of a small runner, item 1, provided on the generator shaft at each end of the machine close to the main bearing, and against each face of the runner a conventional babbitt thrust bearing, item 2, is held by springs, item 3, permanently set to give a pressure equal to about a third of the normal capacity of the bearing. Around the inner periphery of each thrust bearing, but separated from it by a groove, is a continuous babbitt face about an eighth of an inch wide. During operation this continuous face provides the required seal, since it is

Figure 5. Shaft seal



separated from the runner by only the thickness of the oil film in the thrust bearing. Oil under pressure is circulated around the flange between the two thrust-bearing faces to provide cooling and lubrication and to oppose the pressure of the hydrogen at the small clearance between the continuous babbitt face and the flange. The oil pressure counterbalances the spring pressure so that resulting bearing load is very low. Cup leathers, item 4, are provided at the outer periphery of the oil chamber to retain the oil and provide flexibility.

The Allis-Chalmers type of seal is suitable for operation with hydrogen pressures from zero up to ten pounds per square inch without oil or seal adjustments.

As this type of seal provides an air-tight joint, air or gas can be removed from the generator by evacuation. This makes it practicable to simplify the scavenging process described by authors to the extent of eliminating the use of carbon dioxide and offering advantages such as;

1. No carbon-dioxide or other inert gas is required for scavenging generator.

2. Since interchange of hydrogen and air takes place at one fifth of an atmosphere or less, only about one fifth as much excess hydrogen above one volume is required.

3. Extra pipes to drain all "pockets" of carbon-dioxide are not essential.

4. Less time is required to empty or fill generator with hydrogen.

5. The filling operation is simplified.

Operating experience, over a period of months, further shows that the sealing oil volume which gets into contact with the generator hydrogen is so small that oil treatment becomes unnecessary except for its passing through a hydrogen detraining tank before it is returned to the oiling system.

It is expected that additional operating experiences will result in further simplifications in the application of hydrogen as a ventilating medium.

Philip Sporn (American Gas and Electric Service Corporation, New York, N. Y.): Early in 1935 studies indicated the desirability of installing at Logan, W. Va., a 40,000-kw 3,600-rpm high-pressure superposition turbine, in order most economically to develop and increase the capacity of the existing power plant at this location. At that time the manufacturer stated that cooling of the rotor for a generator of this size and speed could be accomplished only by utilizing hydrogen ventilation. Following our extensive and successful experience with seven large-capacity hydrogen-cooled synchronous condensers then in service on the American Gas and Electric Company system, we unhesitatingly accepted hydrogen cooling for this new generator unit. In the case of synchronous condensers, the bearings are entirely enclosed in the outer shell, and therefore the problem of sealing the shaft against gas leakage is not encountered. However, extensive tests and factory operating experience with the oil seal at Schenectady over a period of years, provided a basis for anticipating satisfactory performance from this shaft-sealing arrangement in power-station service.

The Logan generator went into operation as a hydrogen-cooled machine on December 2, 1937, and from that time until February 28, 1939, the unit has run a combined total of 232 days. The running time lost during this period has not been occasioned by any trouble or maintenance in connection with the generator proper or its gas sealing system. No difficulty of any great importance has been experienced with the shaft-sealing system and its accessory equipment. No failure to maintain the seals has occurred at any time. As of February 28, 1939, this seal system had operated 308 days. We are now maintaining a purity varying from 99 to 100 per cent and the gas consumption is averaging approximately 40 cubic feet per day. The delivered cost of this gas, including handling of the cylinders, amounts to approximately 2 cents per cubic foot, so that the yearly cost on this basis is less than $300.

Mr. Snell describes in his paper the pad cooling arrangement for direct water cooling of the stator. Plant condensate was used as make-up for this pad liquid system. In order to eliminate the possibility of air pockets in the pads, it is necessary to obtain a high vacuum before filling with condensate. In this respect some difficulty was experienced initially but by circulating the pad liquid for some time and by wasting a portion from the overhead expansion tank, it was possible to remove practically all of the air still remaining in the pads. The operation of the system has been entirely satisfactory.

Mention is made of operation at gas pressures as high as 15 pounds per square inch. The Logan unit has been run for short periods at these higher pressures with satisfactory performance of the shaft-sealing system and without obtaining excessive consumption of gas. We have had considerable experience with the operation of hydrogen-cooled synchronous condensers at pressures up to and including 15 pounds per square inch. We hope to present detailed operating data covering such performance in a coming paper before the Institute.

D. S. Snell: I wish to thank Mr. Fechheimer for his interesting and valuable discussion. Mr. Fechheimer has contributed much to the development of hydrogen cooling and his comments on the subject are welcomed. As to the saving effected with hydrogen-cooled generators of the 1,800-rpm type through making the machine structure strong enough only for normal operation, but not strong enough to withstand an explosion, I believe that for the type of construction employed with our hydrogen-cooled generators no saving would be obtained. For with a construction in which the generator bearings are supported in the end shields, a construction that is rigid enough for ordinary operation is also strong enough to withstand an explosion. At the present time the cost differential between the hydrogen-cooled and the air-cooled machine is principally due to the cost of the auxiliary equipment, and as this cost does not vary greatly with different sizes of machines, it is difficult at the present time to justify the use of hydrogen cooling for generators in sizes much smaller than the minimum sizes mentioned in the paper.

Regarding Mr. Fechheimer's proposal that ingoing water temperature rather than ingoing gas temperature be used as the reference for basing temperature rises for hydrogen-cooled machines, we have given considerable thought to this matter but still feel that the use of the ingoing gas temperature offers the best basis for making guarantees on this type of machine. The use of the ingoing gas temperature as a basis for temperature rise allows an accurate comparison between different machines as the true rise of the machine alone is obtained, whereas if the ingoing water temperature were used as a basis, a designer could skimp the design of the generator and use an extra large cooler, obtaining the same over-all temperature rise with this machine as with a machine of more liberal design. Obviously the machine with the lower temperature rise within itself is the more liberal design.

Also, since it is easy to test the coolers and the generator separately, there is little or no reason to combine the two in one over-all guarantee, and especially is this true due to the fact that the generator is the major portion of the investment and the more critical.

The Institute at the present time has adopted the ingoing gas or air as a basis for the ambient temperature on which rises should be predicated, and we can see no reason for the Institute's making two different standards for large rotating equipment because one happens to be enclosed and the other an open machine, as basically the temperature rises, which are satisfactory for one machine are applicable to the other type.

Regarding the thickness of the stator iron packages and the armature current density in the hydrogen-cooled machine, both these quantities have been increased over their values for the air-cooled machine.

Mr. Fechheimer's suggestion that the increase in rating of a generator by the use of hydrogen should be considerably greater than the 20 per cent mentioned in the paper, based on the data given in table I, neglects the fact that the hydrogen-cooled generator must be proportioned differently than the air-cooled machine, to obtain the same electrical stability. If this change in design is considered it will be found that the increased output per pound of material with hydrogen will be of the order of 20 to 25 per cent.

Regarding the use of diffusers in conjunction with the centrifugal fans employed with these machines, while these are generally provided with air-cooled generators they have been omitted from many of the hydrogen-cooled machines for the reason that fan efficiency is relatively unimportant in a hydrogen-cooled machine, while the reduction in machine length obtained by omitting the diffusers is of value. This omission results in a rather high windage loss and temperature rise of the air when the machine is operated in air, as Mr. Fechheimer has observed in connection with table I; however, since these machines are intended principally for operation in hydrogen, this feature is not considered important. As to the relative merits of centrifugal and propeller fans, we recognize that while the propeller fan has a slight advantage in efficiency it also requires a greater amount of axial space on the shaft for its support, thus increasing the distance between bearing centers.

Referring to Mr. Fechheimer's inquiry as to the construction of the machine illus-

trated in figure 9, figure 6 of this discussion illustrates the construction of the metal pads which are employed for removing the heat from the stator core and the cooling gas. The pads of the plain type are used in the end sections of the stator core and remove the generated heat by direct conduction to the cooled pad. The finned pads are used in the center part of the core and absorb heat both by conduction through contact with the laminations, and by convection, through passage of the heated gas from the air gap to the back of the core between the fins. The finned pads take the place of the surface gas coolers used with the ordinary type of generator. The fan pressure required to ventilate this type of machine is practically the same as is required with the ordinary type, for the same volume of gas circulated.

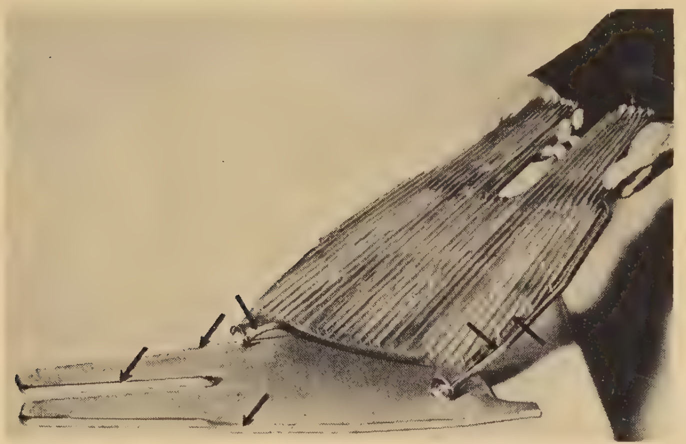


Figure 6. Monel-metal cooling pad for hydrogen-cooled generator, copper-brazed

Arrows indicate brazed joints

It is true, as Mr. Fechheimer suggests, that the development of the hydrogen-cooled machine has been accelerated by the progress previously made in methods of calculating fan performance and ventilation characteristics, and also, I would add, in methods of predetermining the thermal behavior of electrical machines. For much of this progress we are indebted to the researches of Mr. Fechheimer.

The shaft seal described by Mr. Mortensen possesses many desirable features. Several years ago we tested a seal of a somewhat similar type, in which a stationary carbon ring pressed axially against a runner carried on the shaft. Trouble was experienced, however, through air being pumped into the generator casing between the ring and runner by centrifugal force. In Mr. Mortensen's seal this pumping action is prevented by supplying lubricant to the rubbing surface under pressure.

While it is desirable to eliminate from the sealing system as many auxiliaries as possible, the elimination of the vacuum tank, as suggested by Mr. Mortensen has certain disadvantages. Without the use of vacuum-treated oil in the shaft seals, the hydrogen purity in the generator casing will decrease, even if at a slow rate, and the operator must manually scavenge the casing at intervals in order to maintain the desired hydrogen purity. If the oil is vacuum treated, however, no scavenging is required. Also, the vacuum treatment of the sealing oil, aside from its value in the operation of the hydrogen system, is of definite value with respect to the operation of the bearings of the turbine generator set, since vacuum treatment of oil removes impurities and thereby prolongs its life. Considering that the vacuum tank requires little space and practically no servicing, it does not seem that the elimination of this device offers as many advantages as its retention.

The evacuation of the generator casing before filling with hydrogen, or when emptying, as proposed by Mr. Mortensen, has some advantages over the use of an inert gas. However, to evacuate the casing requires that the generator be at rest, whereas the inert gas may be introduced with the generator rotating, which is frequently done to save time.

Messrs. Hill and Berberick mention the problem of contamination of the hydrogen by moisture given up from the sealing oil as being of equal importance to the problem of contamination by air from the oil. While this is probably true where the temperature of the oil leaving the seals is in the neighborhood of 100 degrees centigrade, it is not the case where the temperature of this oil is approximately 60 degrees centigrade, as is the case with the type of seal described in my paper. Since the radial shaft clearance of this seal is the same as that of the bearing the energy loss in the oil film is low compared with the oil flow so that only moderate oil temperatures are obtained. This precludes the possibility of moisture being vaporized out of the oil into the generator.

Mr. Beckwith suggests the elimination of the hydrogen relief valve. In the system described in my paper a relief valve of the mercury type is used to prevent the discharge of hydrogen into the air detraining tank in the event of excessive pressure in the casing. In our later designs a diaphragm type of relief valve is used, which serves also for scavenging. In our case this valve can hardly be dispensed with.

The hydrogen requirement for these machines has been found to vary approximately with the square root of the hydrogen pressure, as stated by Mr. Beckwith, although theoretically the part of the hydrogen requirement due to absorption in the sealing oil should vary about directly with the absolute pressure. The discrepancy is probably due to a slight opening-up of the casing joints at the higher pressures. Tests on the Logan 50,000-kva generator showed a hydrogen requirement of 40 cubic feet per day at one-half pound pressure and 300 cubic feet per day at 15 pounds.

Mr. Sporn describes operating experiences with the Logan generator, which was one of the first hydrogen-cooled generators to be placed in service. It is gratifying to us that this machine, which embodied two radical departures from conventional design-hydrogen cooling and pad cooling—should have operated practically without trouble since installation. Mr. Sporn's company has been a pioneer in the use of hydrogen-cooled machinery, having installed in 1928 one of the first hydrogen-cooled synchronous condensers and in 1937 one of the first hydrogen-cooled generators. His faith in this new development has contributed largely to its success and it is gratifying to us to see that his confidence in hydrogen cooling has been justified.

Mr. Alger mentions a theoretical study made to determine the desirability of using a mixture of helium with hydrogen to reduce the explosion pressure. At the time this investigation was made the cost of commercial helium was approximately six times the cost of hydrogen. Since then the cost of helium has been greatly reduced and it can now be obtained for approximately twice the cost of hydrogen. Even with this reduction in cost, however, the use of helium as a cooling agent is not considered desirable since its cooling properties, as explained in the paper, are considerably inferior to those of hydrogen. Since the type of generator construction and the shaft-sealing and gas-control equipment would be substantially the same whichever cooling medium were used, and the helium-cooled generator would be appreciably larger than the hydrogen-cooled machine for a given output, it will be evident that the use of helium is not economically advantageous.

Mr. Freiburghouse has mentioned some of the recent improvements that have been made in the design of the hydrogen-cooled generator, also some of the details of construction of the 137,500-kva hydrogen-cooled generating set for the Ford Motor Company. This generator set has recently been placed in service with hydrogen. The shaft seals used with these generators are of a different type from those used with our earlier generators and consist of metal rings bearing radially on the shaft, the rings being supported in a housing attached to the end shield. This type of seal requires less oil than the type described in the paper, so that smaller treating tanks and equipment may be used.

Besides the Ford generators, two other hydrogen-cooled generators have been placed in service by our company since my paper was written. We have now 12 of these machines in operation, their combined rating being 770,000 kva. The largest 3,600-rpm machine is rated 66,667 kva while the largest 1,800-rpm generator is rated 176,470 kva. A total of 19 hydrogen-cooled generators are under construction at the factory, with a combined output of 1,035,000 kva. One of these units is rated 50,000 kva at 3,000 rpm and will be installed at Buenos Aires. This is the first hydrogen-cooled generator to be sold for foreign installation. The growing popularity of this new type of generator indicates that the former apprehensions regarding hydrogen cooling have been largely dissipated by the successful operation of the units now in service and that the many advantages of hydrogen cooling are becoming widely recognized.

Some Factors in the Mechanical Design of High-Speed Turbogenerators

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Synopsis: The following paper deals with the approach and the results obtained by advanced engineering technique applied to a few of the problems in large high-speed turbogenerator rotor design. Research and design details incidental to yoke vibrations, application of hydrogen for ventilation, etc., may be dealt with in a future paper.

PROGRESS in steam-turbine design combined with the rapid upturn in power requirements experienced in 1936–37, created a demand for high-pressure high-temperature steam-turbine units of large capacity. It is desirable to operate this type of prime mover at the maximum practicable speed and a number of large air- or hydrogen-cooled 3,600-rpm 60-cycle machines were ordered from the company the writers are associated with. As our previous experience was limited to machines of capacities below 9,500 kva, the larger machines presented further problems, making it advisable to check experimentally the reliability of standard and advanced calculating methods to insure reliable machines, and the ground work for the development of larger capacity machines.

As an example of recent-type two-pole 60-cycle generator construction figure 1 may serve, which depicts a 43,750-kw air-cooled turbine generator with a rotor diameter of $33^1/_4$ inches. To limit the axial length of this machine it was designed with external blowers mounted inside the yoke above the armature. The cooling elements for the ventilating air were also made part of the yoke, thereby reducing the external generator space requirements to a minimum.

To keep this paper within bounds, it will deal only with three of the many factors investigated, which, in the following, are discussed in the order of their original consideration:

1. The determination of critical speeds[1,2] by test for comparison with calculations for symmetrical- and unsymmetrical-section two-pole rotors.
2. Stress analysis of the generator rotor body.
3. Analysis of the lubrication characteristics of the generator bearings to determine maximum bearing efficiencies.

A. Vibration Analysis of Long Rotors

To investigate the accuracy of critical-speed calculations and the vibration behavior of long turbogenerator rotors, a shaft model was constructed having scalar dimensions similar to 3,600 rpm turbogenerators. This rotor model was operated at various speeds, and the vibrations of the shaft and pedestal supports were observed and recorded.

The tests were made for two conditions of the model; first, as a round, symmetrical rotor; and, second, as a two-pole slotted rotor. The maximum shaft diameter was six inches with a 12-foot span between bearing centerlines. It was mounted in $2^1/_2$-inch by six-inch bearings, and driven by a motor having a maximum speed of 4,000 rpm. The weight of the unslotted rotor was 815 pounds and its moment of inertia 63.63.

Following the tests on the round rotor, slots were machined in the shaft model, to obtain a cross section having two moments of inertia at right angles, approximately to the scale of the average

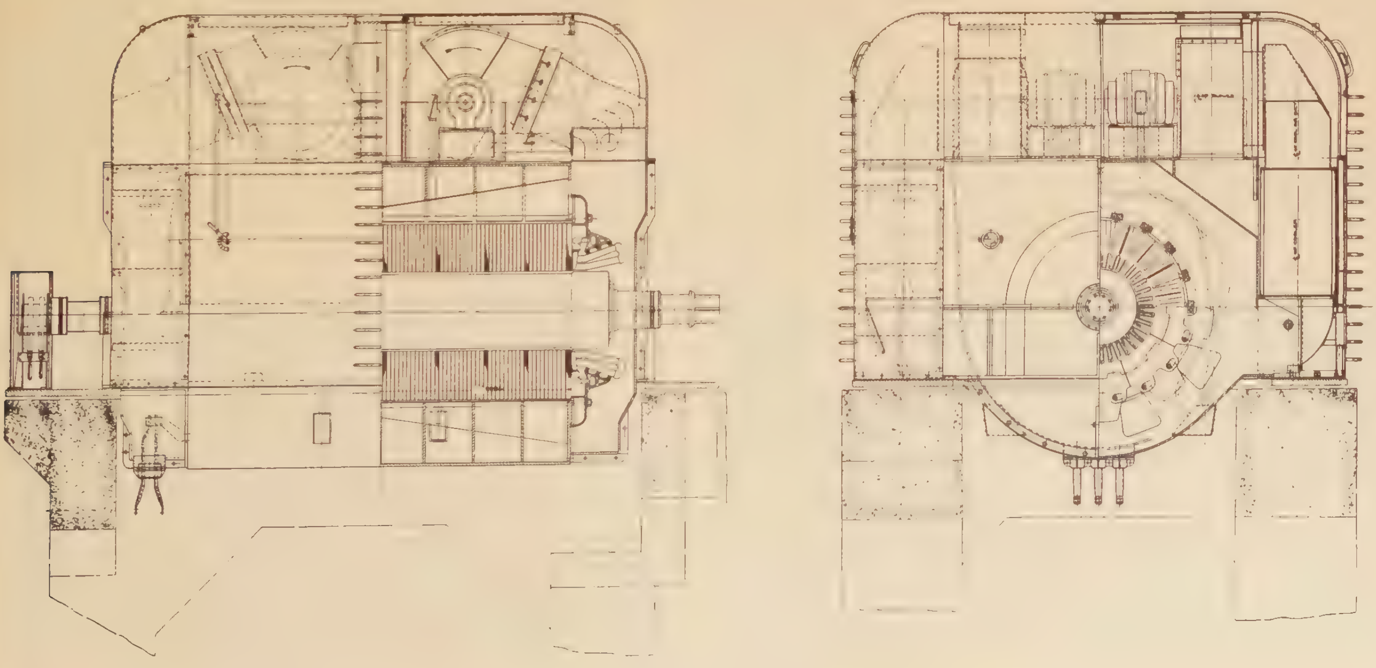

Figure 1. Outline of 43,750-kw turbogenerator

Paper 39-106, recommended by the AIEE committee on electrical machinery, and presented at the AIEE North Eastern District meeting, Springfield, Mass., May 3–5, 1939, and at the combined summer and Pacific Coast convention, San Francisco, Calif., June 26–30, 1939. Manuscript submitted March 8, 1939; made available for preprinting April 7, 1939.

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The co-operation of the steam-turbine department, Allis-Chalmers Manufacturing Company, and the aid of Charles D. Wilson are respectfully acknowledged in the measurement and analysis of the lubrication tests.

1. For all numbered references, see list at end of paper.

Figure 2. View of model shaft—slotted

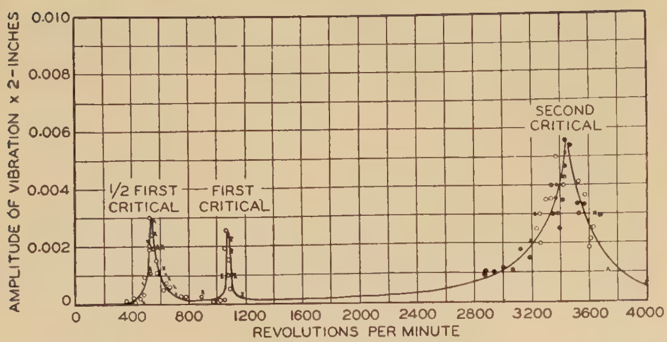


Figure 3. Amplitude-frequency graph of model-shaft vibrations

Two-pole slotted rotor

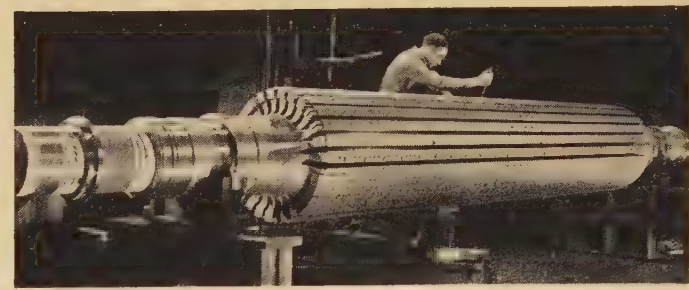


Figure 4. Two-pole turbogenerator rotor

two-pole generator rotor. The slots were cut one-fourth inch wide and one inch deep, spaced $^1/_{28}$ of a circle, with ten slots per pole. The shaft was operated as before and the vibrations observed. A photograph of the shaft after machining is shown in figure 2.

The weight of the slotted rotor was 695 pounds; its maximum moment inertia 52.27; its minimum inertia 42.17.

As stated, the objects of the tests with the model rotor were:

1. To determine experimentally the first (n_1) and second (n_2) critical speeds for comparison with calculated values;

2. To measure the effective flexibility of the pedestals; and

3. To observe the vibration characteristics of the shaft at various speeds.

A Geiger recording vibrograph[3] and a Karelitz vibrometer[4] were mounted on the pedestals to measure lateral and vertical vibrations, and a $^1/_{1,000}$-inch dial gauge was used to check shaft motions. The speed was read on an electric tachometer.

As originally set up, the vibrations of the symmetrical shaft were too small to enable observation of the critical speeds. The rotor was unbalanced a sufficient amount to obtain measurable vibrations. After slotting the rotor for the second tests, it was necessary to straighten the shaft, and balance was obtained by placing plugs in balancing holes. At the final balance, the critical speeds could not be detected, and a slight unbalance was restored.

The calculated and measured critical speeds compared as follows:

	Calculated	Test	
		Horizontal	Vertical
Symmetrical rotor	n_1 = 1,060	n_1 = 1,080	1,085
	n_2 = 3,400	n_2 = 3,280	3,370
Slotted rotor	n_1 = 1,072	n_1 = 1,074	
	n_2 = 3,497	n_2 = 3,430	

In figure 3 are plotted the values of the measured total vibration of the outboard pedestal in a horizontal direction at various speeds for the slotted unsymmetrical rotor. The existence of three critical vibrations were established with no other disturbances in the running range. The amplitudes of vibration were proportional to the arbitrary unbalance conditions.

Conclusions from the above tests indicate that:

1. The maximum difference between the calculated and measured critical speeds is about three per cent, which is representative of the general accuracy of this type of calculation. It may be assumed that on full-scale machines the calculated critical speeds are within the limits of test measurements. The average moment of inertia of the slotted rotor section is the effective moment of inertia for the critical-speed calculations.

2. For the symmetrical rotor, the pedestal flexibility has no appreciable effect on the first critical speed, and only about a three per cent reduction in the horizontal direction over the vertical at the second critical. This quantity is representative of the effect on full-size apparatus, and is maintained by requiring rigid foundations and sturdy bearing pedestals.

3. Running the shaft at various speeds to observe the vibration characteristics indicated that no appreciable vibration occurred except in the immediate vicinity of the criticals. For the slotted rotor, a subcritical was evident at one-half the first critical speed, due to the variable moment of inertia of the shaft. As shown in the vibration curve, figure 3, the slotted rotor would operate as well above the second critical speed as between the first and second. Thus it may be further concluded that very long turbogenerator rotors operating normally above the second critical speed would be entirely practical from a vibration, balancing, and critical-speed standpoint. The present critical speeds for 3,600 rpm turbogenerators could be reduced from 1,600 and 5,000 rpm, respectively, to 900 and 2,700 rpm, making possible a considerable increase in generator capacity with

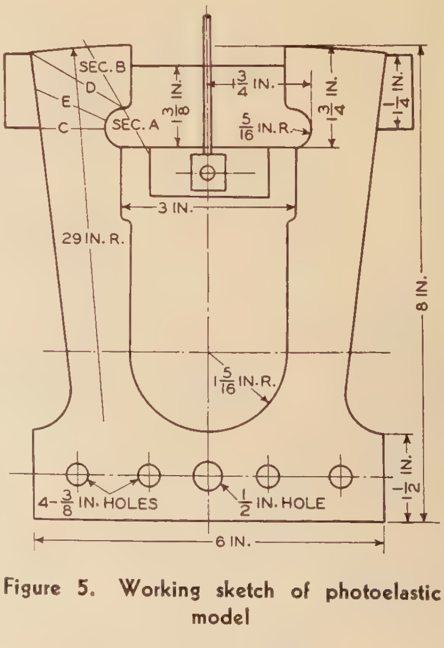


Figure 5. Working sketch of photoelastic model

Transparent Bakelite

added flexibility in design. Such a trend may be anticipated for future consideration.

B. Rotor Stress Analysis

The electrical output of a turbogenerator is roughly proportional to the amount of field copper which may be safely imbedded around the periphery of the rotor. Figure 4 shows the general construction of the type of rotor considered. The teeth between the radial coil slots must be adequate to carry magnetic flux, withstand mechanical stresses, and also carry vent ducts.

To obtain the most efficient and safe design, the stress in the rotor must be accurately known at every point, and the maximum stresses at overspeed of 20 per cent must not exceed the elastic limit of the material.

The area having the most complex stress distribution occurs at the outer extremity of the teeth, at which point slot wedges transfer the centrifugal forces of the winding to the teeth. Further, the bore stress of the central exploration hole is usually of great importance. The following paragraphs discuss the manner in which the stresses were analyzed to obtain the most effective design.

1. Design of Rotor Teeth and Wedges

To determine accurately the centrifugal stress distribution in the rotor teeth and wedges due to the windings, the photoelastic method of analysis was applied. Several transparent Bakelite models were made of the proposed designs to a scale approximately twice full size for use in a large photoelastic polariscope.[5] With load applied under the wedge the respective stress distributions showed the effect of the changes in curvature of the slot wedge fillets. The photoelastic isochromatic pictures determine the difference of the principal stresses while the sums of the principal stresses were measured at points on the sections by means of a thickness-indicating device employing a Huggenberger Tensometer.[6] Configurations giving unpredictable stress concentration were discarded.

A sketch of the final wedge model, its general dimensions, and method of loading in the testing machine is shown in figure 5. A steel bar is clamped between the vent wedges to simulate the built-in condition of the rotor section.

The photoelastic stress distribution[7] for the final tooth and wedge element is shown in the isochromatic picture, figure 6. The stress concentrations along the contact surfaces are entirely removed and a uniform distribution of loading is obtained. The maximum shear stresses on these sections for the preliminary and final designs are shown in figure 7, the latter being indicated by prime letters. An immediate comparison of the effectiveness of the final design was observed by counting the number of bands or fringes proportional to the shearing stress. The maximum tensile stress at the fillet of the tooth, section C, was only slightly lowered by the increase of the fillet radius.

To further decrease these stresses the surface area in contact under pressure was increased by slightly reducing the slot width above the wedge, and the vent slot was made narrower to increase the minimum tooth section. The wedge stresses were not adjusted further since materials for that section are available with any desirable elastic limit.

Standard calculations for the revised design, considering compression, bending, and shear, checked very closely with the photoelastic stress analysis. For the minimum section (section C) of the tooth in tension, however, the photoelastic stresses were approximately 30 per cent higher than the calculated stresses; thus it would be assumed that the

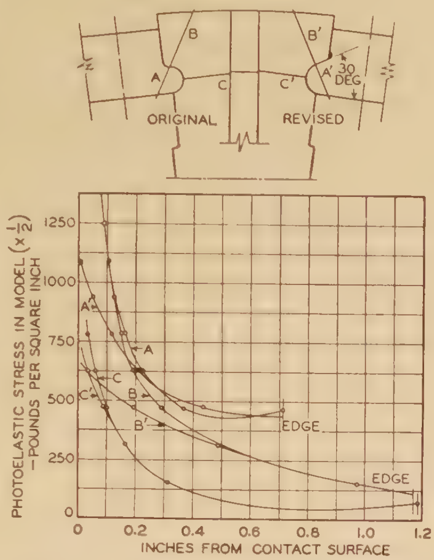


Figure 7. Curves of maximum shearing stresses for original and revised sections

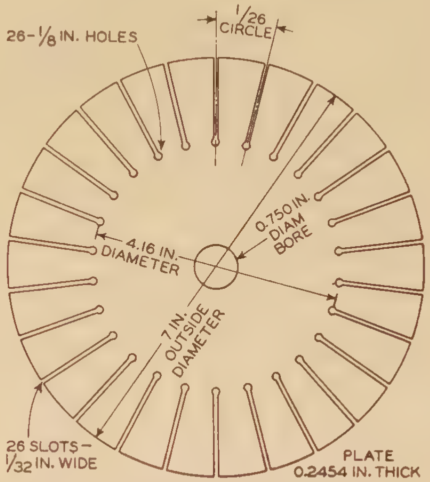


Figure 8. Sketch of photoelastic model of rotor section as rotating disk

Figure 6. Photoelastic picture—revised winding slot wedge shape

Figure 9. Photoelastic picture—rotating disk at 9,200 rpm

stress concentration at the fillet is 1.3.

The applications of these tests in the design of machines have resulted in structures which are completely and accurately analyzed, and for which the maximum stresses do not exceed the elastic limits of the forging materials. Further adjustments may be made in the development of larger machines based upon the data obtained in this analysis.

2. Rotor Bore Stresses

In determining the tangential stresses at the surface of the exploration hole bored in the center of turbogenerator rotor forgings, it is ordinarily assumed that the centrifugal loads on the teeth and the teeth themselves act as a uniformly distributed external loading on a thick cylinder equivalent to the net rotor section. On the stresses obtained in such a thick cylinder are superimposed the stresses due to rotation of the net rotor section as a rotating disk.

To verify the accuracy of the above assumption a model of a section of a 37-inch-diameter turbogenerator rotor body having $7^1/_2$-inch deep slots and a four-inch diameter hole at the bore was made of transparent Bakelite to a reduced scale for test at high speed.

After the disk was machined as shown in the sketch, figure 8, it was placed in the light field of the photoelastic polariscope, and pictures of stress taken with the disk rotating at high speed. Figure 9 is an isochromatic photograph of the stress distribution around the bore of the disk for rotation at a speed of 9,200 rpm. A comparison of stress values derived from this record with values obtained by standard methods[8] of calculations coincided closely. As shown in figure 10, the two curves are nearly coincident, and the linear variation from this condition is proportional to the square of the speeds $(9{,}200/9{,}000)^2$.

From the foregoing it may be definitely concluded that the present analytical theory applied to the calculation of stresses in such bodies as turbogenerator rotors gives a high degree of exactness.

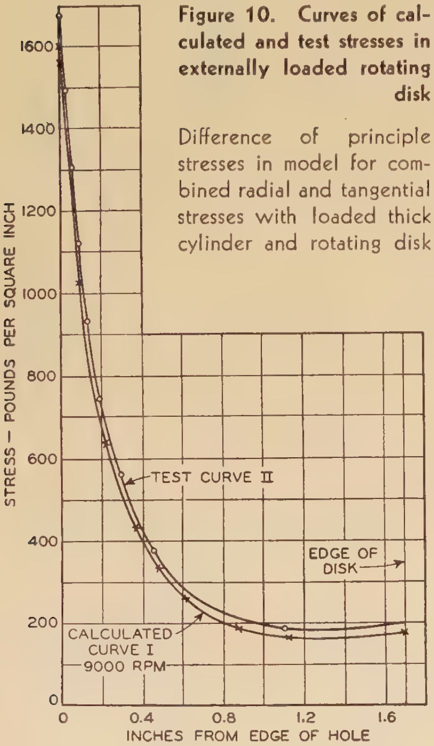


Figure 10. Curves of calculated and test stresses in externally loaded rotating disk

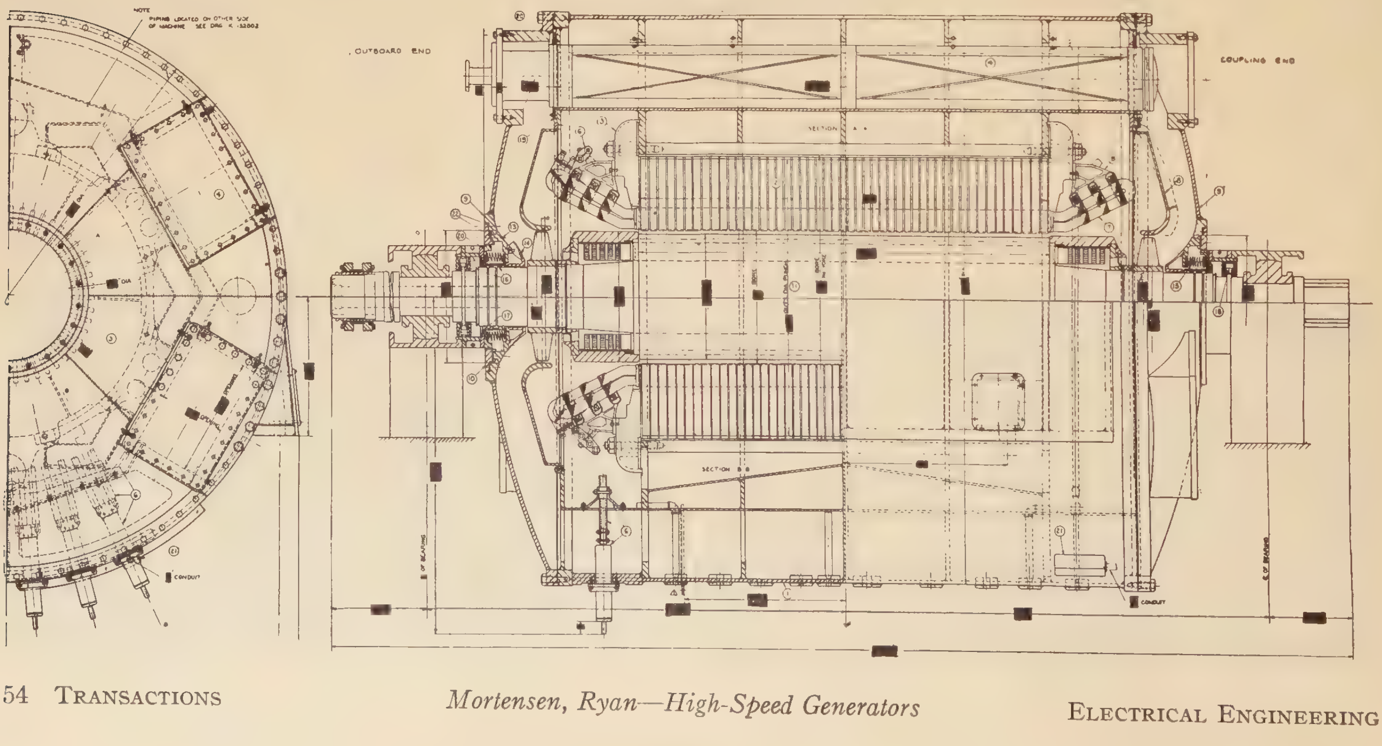
Difference of principle stresses in model for combined radial and tangential stresses with loaded thick cylinder and rotating disk

C. Lubrication Characteristics of Bearings

In addition to the vibration and stress investigations carried out in connection with the development of large 3,600-rpm generators, consideration was given to the various factors determining efficiency. As no promising features appeared for reduction in electrical and magnetic losses, the mechanical features such as windage and bearing friction were investigated. Generator designs based upon hydrogen as the cooling medium were developed. A machine of this kind ordered from the company with whom the writers are associated is shown in figure 11. This machine has explosion-proof yoke and end covers, oil-type shaft seals, and is designed for operating hydrogen pressures up to ten pounds per square inch. It has been in successful commercial operation as a hydrogen-filled machine for several months.

Assuming that hydrogen cooling reduces the generator windage losses to a minimum, bearing losses remain as a possible source for loss reduction. Tests on 43,750-kw 3,600-rpm and smaller machines indicated the possibility of further loss reduction by means of bearing design and lubrication control. For this reason investigations were made of the usual factors of lubrication such as the diameter, length, clearance, and pressure for the journal bearings, and the volume, temperature, and viscosity characteristics of the lubricants. The bearing losses were determined from the heat transfer to the lubricating fluid during circulation through the bearing. The losses due to heat radiation and convection were found small enough to be

Figure 11. Hydrogen-cooled generator, 3,600 rpm, 60 cycles



neglected for comparative purposes.

The generators were driven by a direct-coupled test motor, and test conditions were varied by adjusting speed, oil flow, and oil cooler temperatures. Test data were obtained by readings taken at intervals. In most cases readings were not made until they remained constant for at least 15 minutes. The bearing kilowatt losses were calculated from the test data using density, specific heat values, and viscosities obtained from the oil distributors and checked in the laboratory.

The results of this series of tests may be summarized in the following statements:

It was observed that heat loss was proportional to the volume of oil supplied to the bearings. The curves in figure 12 compare the gallons of oil flow per minute against kilowatt losses for 12-inch by 12-inch bearings, and $13^1/_2$-inch by $13^1/_2$-inch bearings. The points *A* on the curves indicate the normal operating oil flows for the bearings. Points *C* are located to mark the calculated side leakage[9] quantities. The recommended oil flow is arbitrarily set at $2^1/_2$ times the side leakage, points *B*, for safe and efficient operation. Thus excessive quantities of oil forced to flow through the bearings produced high losses which would be considered unnecessary for normal operation.

It was also observed that the bearing losses were in proportion to the average oil temperatures. For all volumes of oil flow, with higher oil-supply temperatures minimum losses were obtained. The curves in figure 13 show a comparison of the losses measured for various quantities of oil flow at two inlet temperatures. Thus for the 12-inch by 12-inch bearing tests above, the kilowatt losses were reduced from 65 to 36 by adjustment of the oil temperature and the quantity of oil flow.

The physical dimensions and other data necessary for the theoretical calculations of power losses in the journal bearings are given in table I.

The calculated kilowatt bearing losses

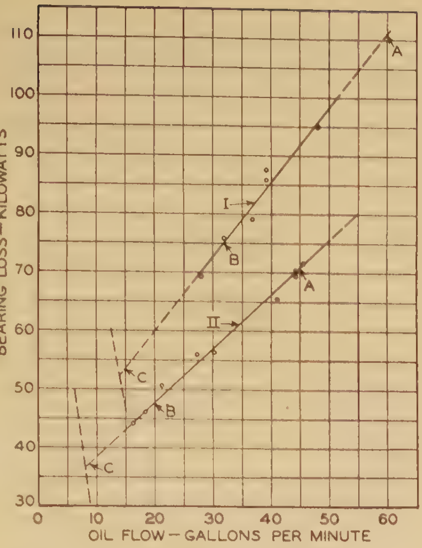


Figure 12. Test curves for bearing loss as a function of oil flow

For 3,600-rpm turbogenerators

Curve I—$13^1/_2$-inch by $13^1/_2$-inch bearing
Curve II—12-inch by 12-inch bearing

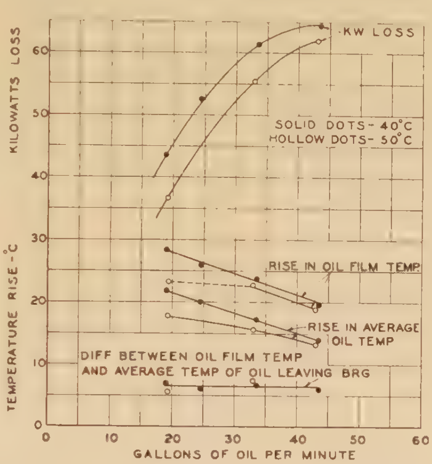


Figure 13. Test curves for bearing loss and temperature rise as a function of oil flow for two inlet temperatures

for the 12-inch by 12-inch bearing, considering only the active portion in the lower half (except for the Petroff equation), are shown in figure 14, for methods by Karelitz,[9] Bradford and Eaton,[10] and Petroff[11], as a function of

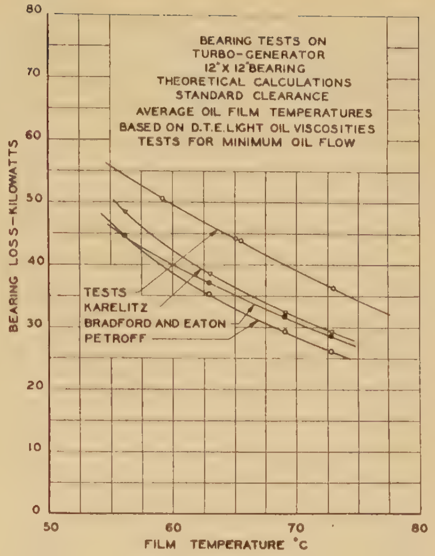


Figure 14. Theoretical calculations and test data for bearing losses with variable oil-film temperatures

average oil-film temperature. Several test points for this bearing with low quantities of oil flow are plotted. From these data it would appear that the measured losses are approximately 25 per cent higher than those calculated by the Karelitz or Bradford and Eaton methods.

Recent tests by Tichvinsky[12] on a 7- by $10^1/_2$-inch bearing at 3,600 rpm would indicate losses identical to those measured above, for a 12-inch by 12-inch bearing at a film temperature of 60 degrees centigrade. However, at 75 degrees centigrade the measured losses were 13 per cent lower than those which would be predicted by Tichvinsky's tests.

As a result of these tests, the following conditions have been established for the efficient operation of large high-speed bearings:

The oil flow to the bearing should be restricted to a safe minimum. An adequate amount is $2^1/_2$ times the side leakage calculated for the bearing. The top half of the bearing is relieved to allow this flow with the least possible pressure resistance and the bearing is designed with additional side relief to maintain an increased oil reserve. The oil supply to the bearing is metered through an orifice from a high pressure oil line, and quantity rather than pressure is the control criterion.

The oil outlet temperature should be maintained between 63 degrees centigrade and 70 degrees centigrade corresponding to thermocouple temperatures in the babbitt between 70 degrees centigrade and 77 degrees centigrade. The higher oil temperature is obtained by reducing the water flow in the oil cooler.

Table I. Bearing Dimensions and Data

Bearing (inches)	$13^1/_2$ by $13^1/_2$	12 by 12
Diameter of journal	13.478	11.980
Diameter of bearing	13.500	12.000
Nominal clearance	0.022	0.020
Nominal length	13.5	12
Effective length (inches)	11.75	10.5
Bearing load (pounds)	25,800	16,400
Bearing pressure (projected) (pounds per square inch)	162.5	130
Speed (revolutions per minute)	3,600	3,600
Bearing angle (deg)	90	90
Nominal oil required (gallons per minute)	60	46
Calculated end leakage (gallons per minute)	13.8	8
Adequate oil supply (gallons per minute)	31.5	20
Nominal bearing babbitt temperature (deg C)	60 (140 deg F)	60
Suggested bearing babbitt temperature (deg C)	77 (170 deg F)	77
Calculated minimum oil-film thickness, 77 deg C (inches)	0.003	.003

The bearing design must take into account the increased temperatures in the allowance of clearance dimensions. Adequate safeguards are to be installed to preserve the oil supply, controlled by thermocouples in the babbitt connected to auxiliary service lines. In this manner it is possible to reduce bearing losses approximately one-half based on the prevalent operating conditions (and effect a 0.3 per cent increase in efficiency at rated load for large turbogenerators). Thus the elimination of losses in the unloaded portion of the bearings due to excessive lubrication, and the decrease in the general viscosity with higher temperatures obtain a closer correlation between theoretical calculations and test data.

Summary

The preceding paper indicates:

1. The practicability of analytically predetermined critical speeds of rotors with cross sections having different moments of inertia at right angles.

2. The value of the photoelastic method for stress determination in rotating bodies.

3. The possibility of increased machine efficiencies by control of bearing lubrication.

As a résumé of the tests and calculations described, it is believed that in the recent development of large machines, efficient and strong structures have been realized and the door opened for the design of larger and more efficient generators.

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11. THEORY OF LUBRICATION (a book), **M. D. Hersey.** John Wiley and Sons, Inc., New York, 1936, page 38.

12. TESTS OF A 7- BY 10 1/2-INCH BEARING AT 3,600 RPM, **L. M. Tichvinsky.** ASME *Transactions*, volume 60, number 5, July 1938, page 395 (figure 6).

Discussion

Sterling Beckwith: See discussion, page 34.

B. A. Rose (Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): The paper discusses the vibration of a generator rotor at the first and second natural frequencies, and for each of these frequencies the nodal points (points of zero vibratory motion) of the vibrations were very probably at or very near the center of the bearings or at certain spots in the pedestal structures themselves. We have found that a higher mode of vibration can exist such that the nodal points are located very close to the ends of the rotor body. The frequency at which resonance will occur is quite high, being of the order of 7,200 cycles per minute. This mode of vibration is not excited by the unbalance of the rotor because its natural frequency is well above the rotational frequency of 3,600 rpm. However, it is apt to be excited by the double-frequency vibratory force caused by the nonuniform rigidity of the rotor body and, therefore, should be taken into consideration in the design of generators of this type.

H. D. Taylor (General Electric Company, Schenectady, N. Y.): With regard to the three-to-one relationship between the second critical speed and the first critical speed observed by the authors on their test rotor representing a long turbine generator, this agrees quite well with data secured by the writer on a somewhat heavier test rotor weighing about 5,300 pounds. Calculated and test values of critical speeds for this rotor, when running with exceptionally rigid bearing supports, were as follows:

Critical Speed	Calculated	Test Vertical	Test Horizontal
First	1,200	1,200	1,125
Second	4,000	3,900	3,250

It may be noted that the criticals in the vertical plane checked with calculations very closely, but that in the horizontal plane the first critical was reduced about 6 per cent, and the second about 17 per cent, due to slight horizontal flexibility.

We have also had experience with light rotors weighing up to 600 or 800 pounds, which showed little or no reduction of critical speeds below calculated values. It is common experience that for the heavy rotors of full-size turbine generators, the first critical is reduced considerably, as much as 20 or 30 per cent below the value calculated for rigid bearings, especially in the horizontal plane. Although supporting data are meager, the writer ventures the opinion that such machines also have a second critical speed reduced a great deal more from the calculated value, so that the ratio of the second critical to the first may actually be, instead of three to one, only two to 1, or even less.

However, there seems to be nothing particularly dangerous about the second critical speed. Tests with the 5,300-pound rotor demonstrated that the amount of vibration experienced at the first critical is a direct function of the amount of "static" unbalance in the rotor, and is not influenced by "dynamic" unbalance or "couples"; likewise, that the second critical responds only to couples, and is independent of static unbalance. A rotor having good static balance runs smoothly at the first critical; and with good dynamic balance, at the second critical also. In other words, good balance practically eliminates these critical speeds.

If a critical speed of 900 rpm is considered for a long generator field, the writer would anticipate the possibility of having a third critical speed within the running range, depressed from a higher calculated value by bearing flexibility. Also the possibilities for other types of vibration such as "whipping," would be greatly multiplied. However, I share the authors' view that lower critical speeds than 1,800 rpm will eventually be found practicable.

S. H. Mortensen and J. J. Ryan: It is assumed that the higher mode of vibration referred to by B. A. Rose is the third critical speed for turbogenerators. The deflection curve for this critical condition has nodes near the ends of the rotor body and at the bearing pedestals. A two-pole rotor with variable moment of inertia would probably set up double-frequency vibrations at one-half the third critical speed.

For a first critical speed of 1,600 rpm, a second of 5,000, and an assumed third of 10,000, the speed necessary to exhibit this type of vibration would be 5,000 rpm for a standard 3,600-rpm turbogenerator.

Such vibration phenomena has not been observed in the operation of these machines, but it is possible, under certain circumstances, this critical condition may be very close to the operating speed.

For the two-pole slotted rotor discussed in the paper it was observed that a double-frequency vibration occurred as the second critical speed was approached. The Geiger vibrograph showed approximately 0.0015 inches total motion at 6,600 vibrations per minute superimposed upon the single-revolution-per-minute frequency of 3,300 vibrations per minute for the maximum recorded motion of 0.003 inch. Since the double frequency disappeared at the second critical speed, it was not considered further.

However, the interesting discussion of H. D. Taylor stimulated the urge to further investigate the effect of the third critical speed, and the slotted rotor shaft was again operated on the test floor. As the second critical speed was approached the phenomena was repeated as above. Calculation of the third critical speed is thus a necessary factor in design to avoid double-frequency resonance of the nonsymmetrical rotor.

Turbine-Electric Textile-Range Drives

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NONMEMBER AIEE

A TEXTILE RANGE—the definition is offered for the benefit of those who may be unfamiliar with textile parlance—consists of a group of co-ordinated machines through which a continuous band of cloth is passed in rope or flat form (figure 1). Carrying on, in a group, the maximum number of operations of a textile finishing process which manufacturing conditions will permit lowers the cost of production by reducing the time and labor costs, and improved methods of driving such ranges may lead to still further increases in the production rate per unit of equipment, with attendant reduction in unit cost of production.

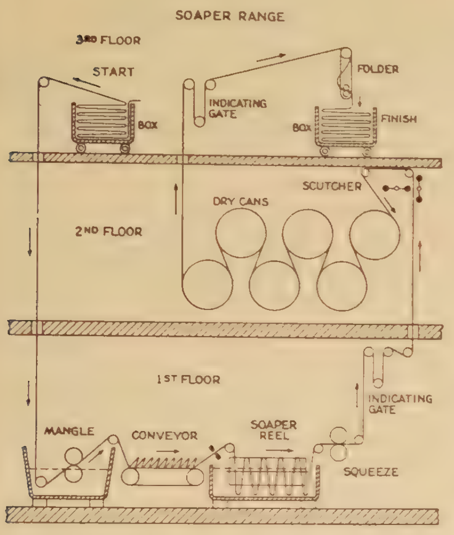

Figure 1. Group of related machines known as a soaper range

As an example of this, we have observed mills in which the cloth was subjected to two successive drying processes, perhaps with an intermediate sizing operation. The cloth was passed through a range and either batched on a roll or folded into a box, after which it was passed through a second range consisting of a starch mangle and dry cans.

Early textile mills were driven entirely by mechanical means, usually by a combination of hydro and steam-engine power. As a textile range almost always included a drying process, the use of steam engines for driving them became general.

It may be noted at this point that ranges are frequently built for processing a wide variety of textures and weights of fabric. Therefore, a range of operating speeds as great as three or four to one is required. In addition, a threading or adjusting speed of perhaps ten per cent of the maximum operating speed for short periods is sometimes desired.

Based on these considerations, engine drive had two important advantages, and some of these drives are still in use.

1. Exhaust steam from the engine was used in the drying process, allowing the driving power to be obtained as a by-product.

2. Throttle control of the engine provided a flexible and inexpensive means of obtaining the desired range of speeds.

It had also, certain notable disadvantages.

1. Losses and maintenance costs resulting from complicated mechanical means of interconnecting sections of the range.

2. Inaccurate speed relation of sections due to belt slippages and nonuniform stretch of different fabrics processed on the same range.

The development of electric equipment and its general substitution for mechanical drive in textile mills led to consideration of electric drive for ranges. Earlier drives of the single-motor type retained some of the disadvantages noted in connection with engine drives. Later drives have been of the multiple-motor type, with basic speed control applied to the motor driving the lead section and motors driving follower sections held in step with the lead motor by compensating gate control. Such drives have been of the variable-voltage d-c type or variable-speed a-c type and have overcome many of the disadvantages common to single-motor and engine drives. It has also been possible to increase the number of sections comprising a range and to locate these sections on as many as three floors of a building when manufacturing reasons dictated the wisdom of such procedure.

Multiple-motor drives have provided an adequate solution of range problems in finishing plants where the efficient use of steam was already effected by the generation of power by turbine generators in a power station, with a low-pressure steam main carried into the mill to meet the demands for process steam.

For plants in which power is not being generated, even though there is a demand for low-pressure steam, the turbine-electric range drive offers interesting possibilities. This drive, in its usual form, consists of a gear-turbine flexibly coupled to a slow-speed a-c generator which has a shaft extension providing some form of mechanical drive for a section of the range then designated as the lead section. The generator is electrically connected to a-c motors, ordinarily of the induction type, which individually or in closely related groups drive other sections of the range (figure 2). Although a new arrangement, the components of this drive are standard pieces of equipment in simple form.

Basic speed adjustment is accomplished by varying the speed of the turbine either by hand or by remote throttle control or by the more expensive means of variable-speed governor control. The turbine satisfies the need for flexibility of speed control, and at the same time its use results in a low operating cost by providing the power needed for driving the range as a by-product from steam required to meet process demands. The fuel cost to supply the heat converted to

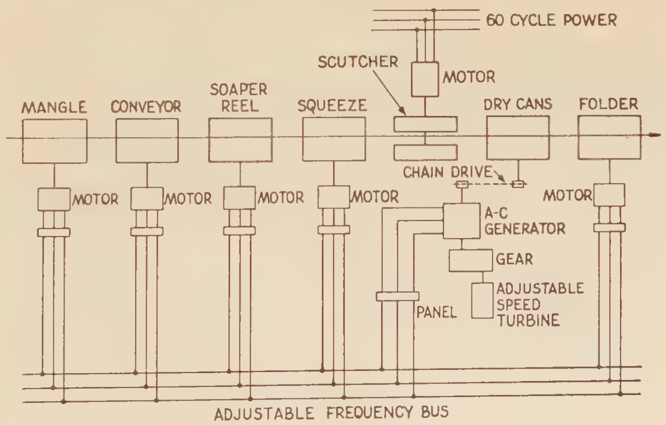

Figure 2. Schematic diagram of turbine-electric drive for a soaper range

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E. L. Richardson is with the General Electric Company, Schenectady, N. Y.

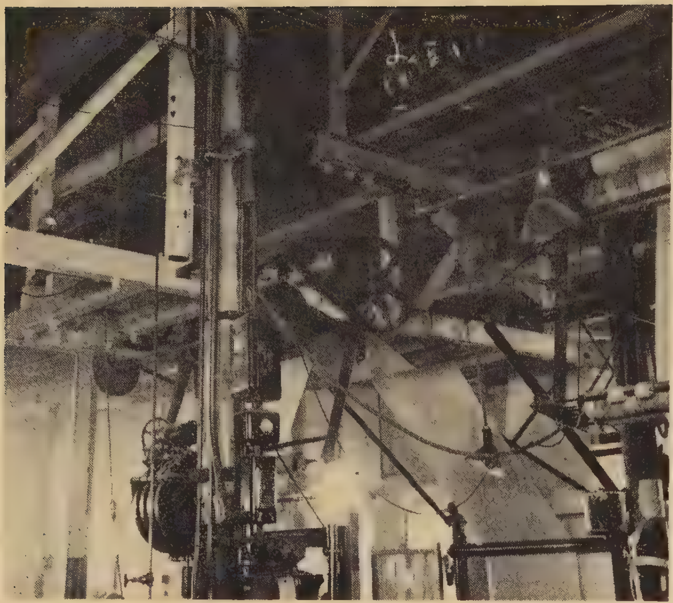


Figure 3. Motor drive to folder. Part of turbine-electric textile range drive in New England mill

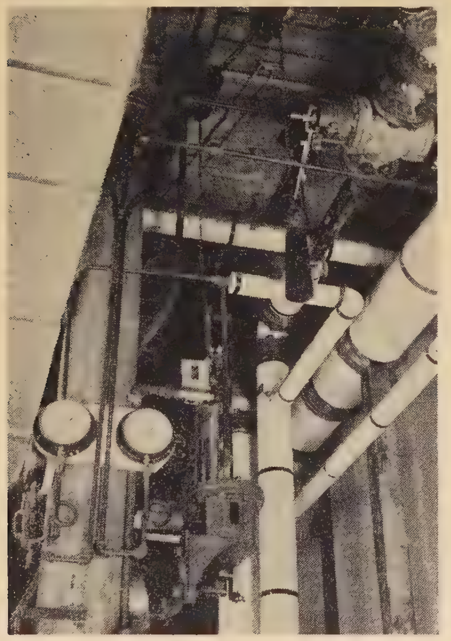


Figure 4. Steam-pressure-regulating and control valve of turbine-electric range drive in New England mill

Figure 5. Turbine generator set, showing mechanical drive to dry cans and centrifugal field-control switch

power in the turbine is usually the equivalent of an electric-power cost of approximately one mill per kilowatt-hour.

With this form of drive, a section can be selected as the lead section on the basis of consideration of space and the convenient location of the prime mover. As this section is driven mechanically, its speed varies in direct proportion to that of the turbine.

The a-c generator, being driven by the turbine, generates a frequency directly proportional to the speed of the turbine and of the lead section. Motors driving other sections and having this generator as their power source are then driven at speeds having a uniform relation to the frequency of their power source except for the effect of motor slip due to load changes.

This effect of motor slip is advantageous because it allows motors to be initially placed in a fixed speed relation to the sections which they drive and yet provide ample flexibility, through a slight amount of belt action between sections, to accomodate the variable stretch factor of different grades of cloth. Special consideration is given to the slip factor and torque characteristics of motors for this application, the amount depending on local conditions to be met.

About a year ago a large New England mill installed a drive of this type which involved many interesting problems related largely to control.

In this case, the dry cans were mechanically driven. As it was desired to warm up the dry cans in motion and to wash them on shut down, with the balance of the range stationary, simple switches were provided to disconnect the follower motors from the generator. This required a range of operating speeds from full speed to one-third speed, but did not demand low speed for threading or adjustment, a fact which somewhat simplified the control problem.

The operator is concerned only with a four-button push-button station. The starting and stopping of the range is controlled by two of these buttons, and adjustment of the operating speed is effected by the other two buttons through a pilot-motor adjustment of valve or governor.

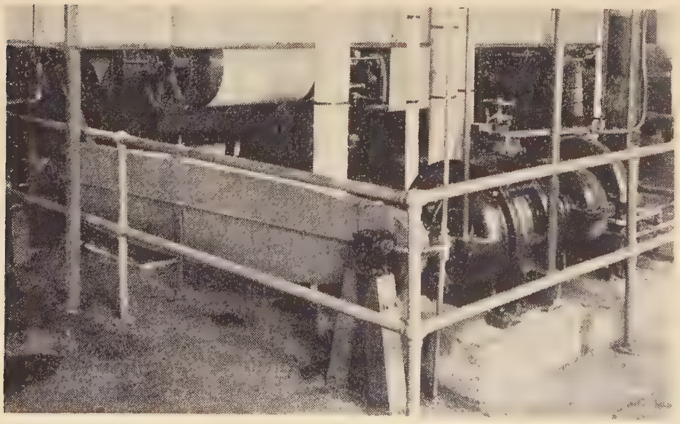
The control cycle initiated by the operation of "start" and "stop" buttons may be of interest. When the start button is pressed, the following steps take place:

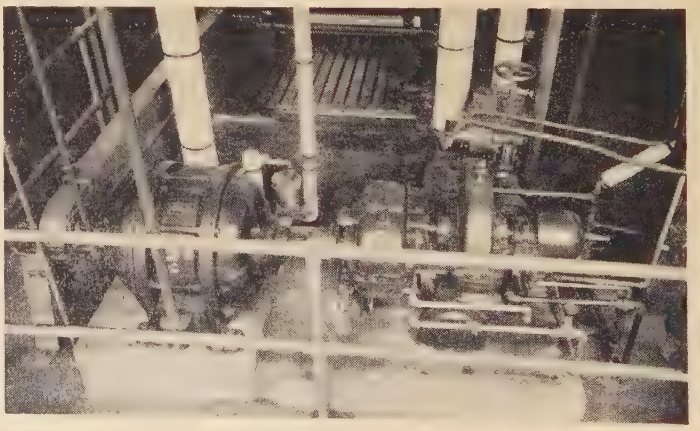
1. A solenoid-operated pilot valve is opened, causing a hydraulic relay to open slowly a valve which admits steam to the turbine, allowing acceleration to a preset speed.

2. The generator field circuit is closed, allowing electrical energy to be generated as soon as rotation starts.

3. The generator field rheostat is short-circuited, thereby applying full field to the generator in order to allow the follower motors to develop maximum torque at very low frequency.

Figure 6. General view of turbine generator set with chain drive to dry cans





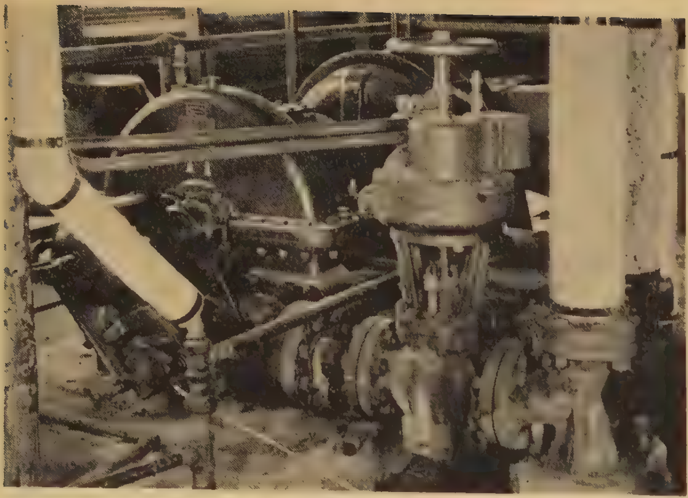


Figure 7. Motor-operated control valve for turbine-electric range drive in New England mill

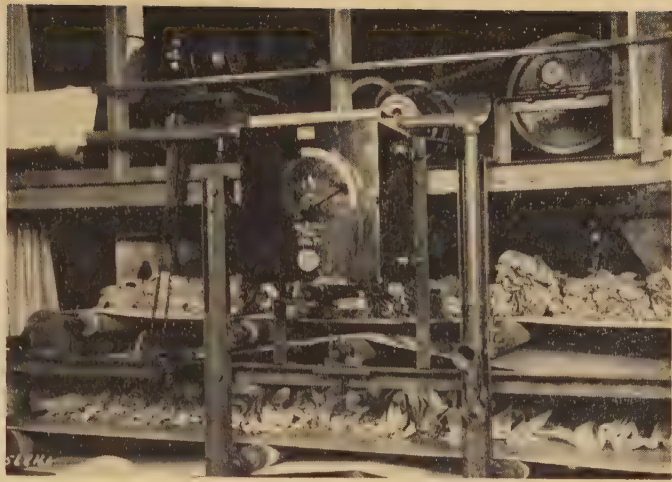


Figure 8. Motor-driven cloth conveyor

4. A timing relay is started which, after a generator frequency sufficient to supply adequate motor torque is reached, breaks the short circuit across the generator field rheostat and thereby reduces the field current to a normal value.

When the stop button is pressed, the following operations occur:

1. The solenoid-operated pilot valve is closed, causing the hydraulic relay to close a valve interrupting the steam supply to the turbine.

2. A magnetic switch is closed. This connects a three-phase resistor across the generator terminals, supplying braking effect for rapid deceleration.

The generator field circuit remains closed until the generator comes to rest, when the field circuit is opened by a centrifugal relay driven by the generator.

Each follower-motor circuit contains a thermal overload relay. The contacts of all these relays are connected in series with the stop button circuit, so that excessive load on any motor will shut down the entire range.

It should be understood that when this type of drive is started, the mechanically driven section starts with the turbine, at which time the voltage and frequency at the generator terminals is at zero.

Carefully conducted tests indicate that follower motors start when the generator frequency reaches a value somewhere between two and three cycles and that there is a time lag of about $1^1/_2$ seconds between the starting of the turbine and the starting of the follower motors.

For this reason it has been found desirable to provide floating rolls, capable of accommodating about three feet of cloth, between the mechanically driven

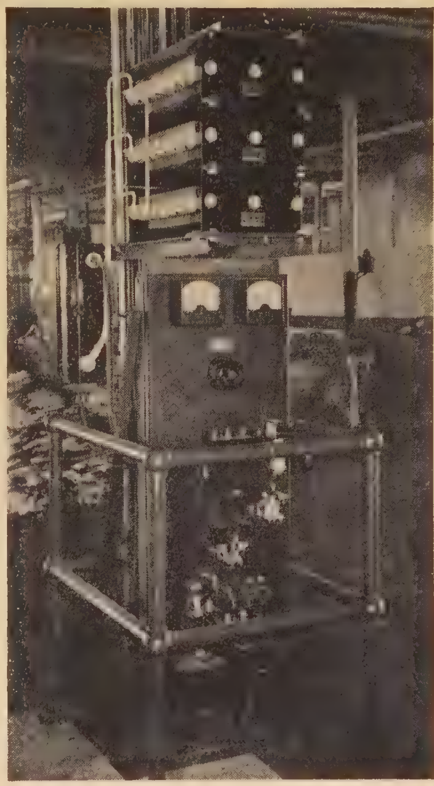


Figure 10. Main control panel for generator and braking resistor

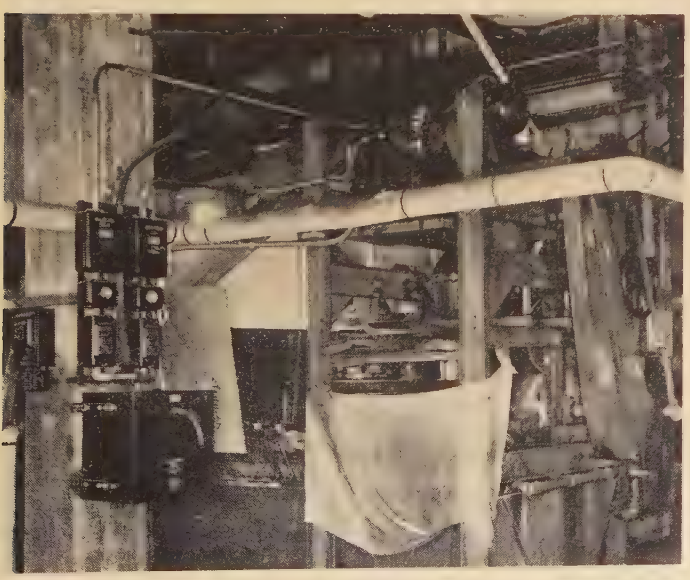


Figure 9. Motor-driven soaper reel. Part of turbine-electric range drive in New England mill

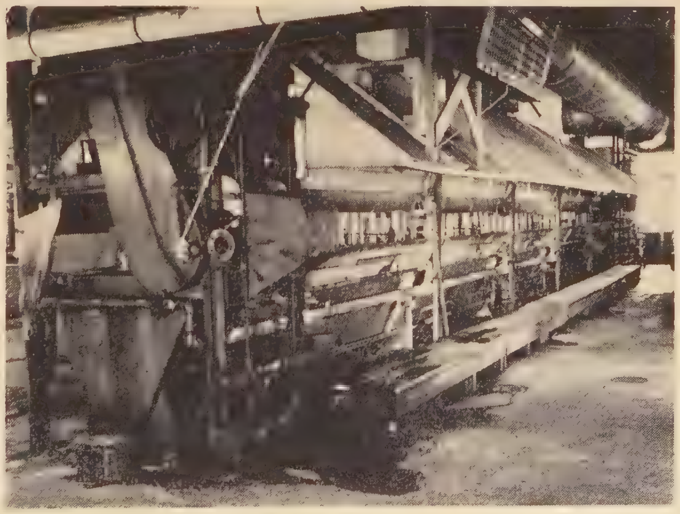


Figure 11. Motor-driven soaper reel

A High-Gain D-C Amplifier for Bio-electric Recording

HAROLD GOLDBERG
ASSOCIATE AIEE

Synopsis: This paper describes a d-c amplifier for use with the cathode-ray oscillograph whose maximum voltage amplification is 6×10^6. This amplification is attained with a noise level referred to the input of less than two microvolts over a 5,000-cycle-per-second band, and without the drift due to variations in battery voltages and circuit constants characteristic of such amplifiers. The amplifier is push-pull throughout and provides a choice of two input circuits. Voltage sources in which both terminals are at a high impedance to ground are connected grid-to-grid, symmetrically to ground, while sources in which one terminal is at ground potential are connected to either grid and ground, the first stage, in this case, acting as a phase inverter. Stability and phase inversion are obtained by means of a circuit that makes the output relatively independent of battery voltage and tube-constant variation. The amplifier is simple and rugged, uses ordinary radio-type tubes which do not have to be carefully matched, is constructed of ordinary radio-type components, and has reasonable battery requirements.

THE PROBLEM of recording the potential-time variations produced by bio-electric phenomena is a difficult one. The maximum potential differences occurring in various biologic preparations range from 10^{-5} to 10^{-1} volts. The potential-time variations themselves range from unidirectional and very low-frequency recurrent types (figure 5) to phenomena whose period is less than a millisecond. The string galvanometer has been used for such work in the past and still has wide acceptance. Its ability to record d-c phenomena and its high sensitivity under proper conditions, 10^{-4} volts per millimeter, make it almost ideal for this work. Recently, sensitivities of the order of 10^{-6} volts per millimeter have been obtained by using low-gain low-noise-level amplifiers with the string galvanometer. Opposed to the advantages of this instrument, however, are its poor frequency response (0–250 cycles per second), its variation in sensitivity with temperature, the fragility of the quartz string in the galvanometer, and its low input impedance when used without an amplifier.

The cathode-ray tube, on the other hand, has none of these disadvantages and with present day tubes and high-speed films, the recording of nonrecurrent biologic phenomena is not difficult even with moderate anode voltages. The cathode-ray tube is inferior to the string galvanometer only in its sensitivity, three volts per millimeter, for a representative three-inch tube with 1,000 volts on its anode. While the string galvanometer, whose sensitivity is 30,000 times as great, can record bioelectric potential differences directly, the cathode-ray tube must be associated with an amplifier to accomplish the same result. In order to obtain a sensitivity of 10^{-6} volts per millimeter, to make use of the high-frequency response of the cathode-ray tube, to be able to reproduce faithfully d-c phenomena, and to have sufficiently low noise level to justify the high sensitivity, one must associate with the cathode-ray tube a d-c amplifier responding to a band width of 0–10,000 cycles per second which has a maximum voltage amplification of 3×10^6, and a noise level, referred to the input, of less than two microvolts over a 5,000-cycle-per-second band.

Such performance requirements, while desirable in an instrument for laboratory research, need not be as severe in special applications such as human electrocardiography as an example. The human heart beats from 70 to 80 times per minute in a normal person, and an amplifier which responds down to one cycle per second will faithfully reproduce the action potential produced by the heart once during each beat. One can construct resistance-capacitance coupled amplifiers that will do this without great difficulty, and such amplifiers are generally used for this work. One could not, however, practically construct such an amplifier to reproduce faithfully phenomena such as presented in figure 5. Such an amplifier would have to have a time constant in the neighborhood of 150 seconds and the coupling capacitors required would be enormous. Since even lower-frequency phenomena occur, the d-c amplifier is seen to be the type that must be used.

If the cathode-ray tube is to be used for this work, therefore, an amplifier must be constructed fulfilling the requirements already stated. The most difficult problem to be solved in the design of such an amplifier is the one of compensating for the "drift" in the operating voltages of the output stage due to small variations in operating voltages and tube constants in the input stage. This problem becomes an increasingly difficult one to solve as the voltage amplification is increased, since the maximum uncompensated residue of the variations in the input stage that can be tolerated becomes smaller and smaller. The amplifier described in this paper solves this difficulty and attains a maximum voltage amplification of 6×10^6, sufficient for a sensitivity of 5×10^{-7} volts per millimeter with a three-inch cathode-ray tube operated with 1,000 volts anode potential. The amplifier is compact, easy to operate and adjust, and inexpensive to construct. Only moderate battery voltages are required and the current drain is very low. It has been found that low noise level and high stability may be attained even with the use of ordinary radio-receiver-type circuit components.

Design and Theory

Noise Level

The 38-type tube, a power output pentode, when operated at very low plate and screen voltages, is a practical amplifier tube possessing very low inherent noise. The noise voltage output of a single amplifier stage using this tube operated as stated, is equivalent to a noise voltage of less than two microvolts impressed on the grid of the stage, pro-

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section and the motor-driven sections.

Experience has shown that, after essential adjustments have been made, this type of drive can be easily and successfully operated by the ordinary finishing-plant operator.

The use of a-c motors simplifies wiring installation and reduces the maintenance expense to a minimum.

Smooth acceleration and deceleration of the turbine-electric drive combined with accurate speed control reduces damage to the fabrics in process, resulting in maximum production.

vided the stage passes no frequencies higher than 5,000 cycles per second. The high emission of the power-type tube makes this tube practicable as a voltage amplifier even at plate voltages and screen voltages of 12 volts and lower. Four such tubes, two per stage, are used in the first two stages.

Amplification

The remainder of the desired voltage amplification is obtained with two additional stages. Four type 6*J*7*G* tubes are used, two to a stage. These are radio-type pentodes of the sharp-cutoff variety. They provide a voltage amplification of about 130 per stage. A plate-supply voltage of 225 volts on the output stage provides for an undistorted voltage output sufficient to cover the cathode-ray screen.

Stabilization

There are two methods, in general, for overcoming the "drift" in operating voltages due to slow variations in battery voltages and tube constants. One method is to provide an automatic means for compensating for such drift; the other, is to make the circuit operating voltages relatively independent of such changes without at the same time destroying the amplifying properties of the circuit. Several circuits have been proposed in the literature for use with the "electrometer" tube in single-stage amplifier circuits. These operate according to the first method. The employment of such means in a multistage amplifier would complicate the operation and adjustment to the extreme.

The second method of attack is more practical for a multistage amplifier and has several advantages. A circuit whose operating voltages are relatively independent of battery voltage and tube-constant variations will be relatively simple to adjust and maintain. The replacement of tubes and aging of batteries will have little effect on amplifier adjustment and performance. Furthermore, there is no necessity for a knowledge of the exact characteristics of each tube to be used in the amplifier as is often necessary in compensation schemes.

The use of push-pull circuits is immediately suggested as a possible means of rendering the steady-state output voltage of the amplifier independent of tube and battery variations. With perfectly matched tubes, any variations in the output due to variations in supply voltages will cancel. Furthermore, the tubes may easily be self-biased without affecting the amplifying properties of the circuit. Such a circuit, however, would not suffice to keep the operating voltages of the output stage at optimum values should excessive changes develop in the batteries supplying the first stages or should matched pairs of tubes be replaced by other matched pairs of somewhat different characteristics. In addition, some provision for phase-inversion would be necessary for use with voltages in which one terminal is grounded unless one would be willing to use only one side of the amplifier for signal voltages.

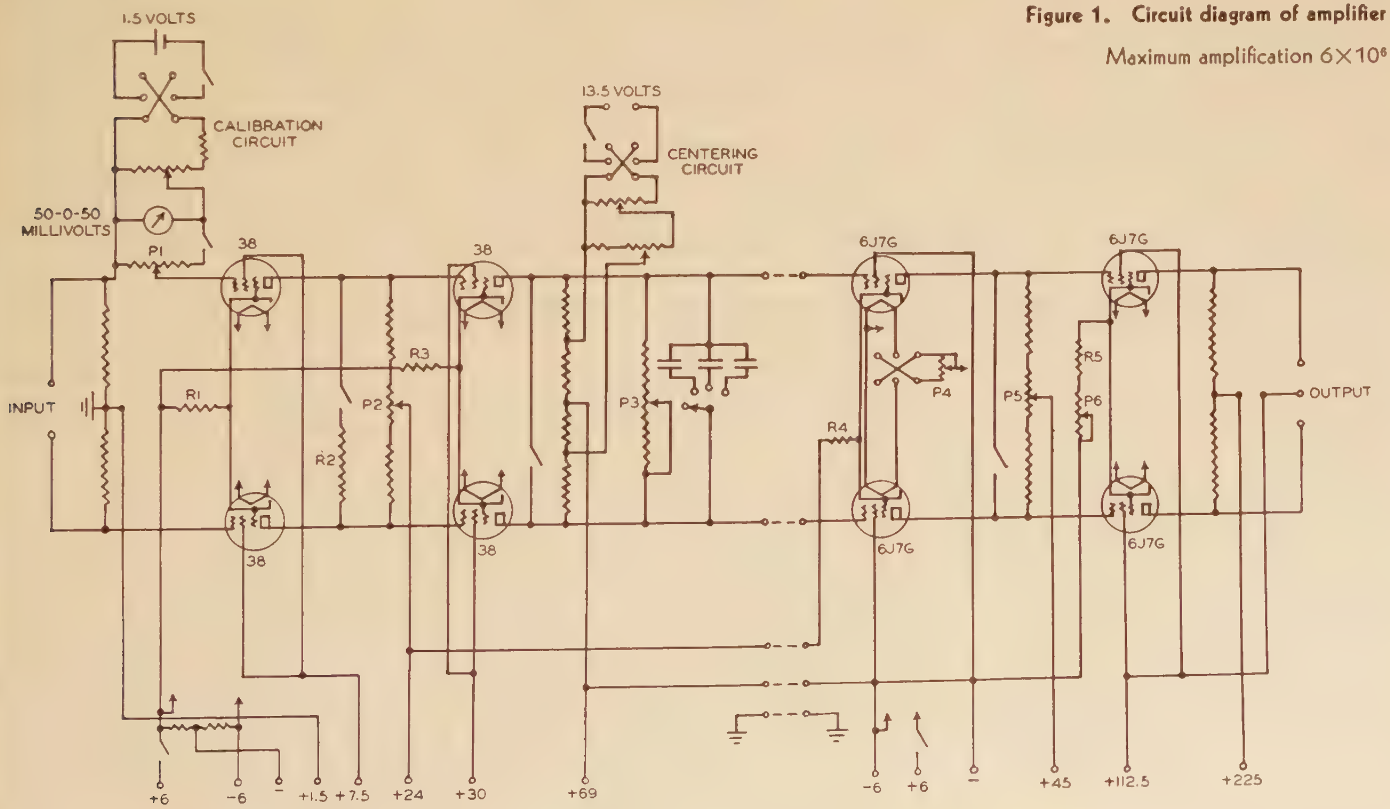
Even if one decides, however, that the last mentioned difficulties are not too important, there remains the fact that in a practical sense, commercial-type tubes cannot be perfectly matched. A push-pull circuit using unmatched tubes will not completely cancel variations in output voltages due to drift but will only partially cancel them, and for that reason the push-pull circuit must be used with additional modifications to take care of the uncancelled residue.

The fact that unmatched tubes must be used brings about still another difficulty. It is desirable to maintain balanced push-pull voltages in all stages ($E_1 = -E_2$ in the arrow directions, figure 2). It will be generally impossible to do this in a simple push-pull circuit that uses unmatched tubes without some circuit modifications. While this balanced condition is not too important in a low-gain amplifier, it becomes increasingly important as the voltage amplification is increased.

The circuit finally used in the amplifier is a modified push-pull circuit in which phase inversion is an inherent property, balanced push-pull voltages are automatically maintained despite tube differences and circuit unbalances, optimum operating voltages are maintained in all stages even under large variations of

Figure 1. Circuit diagram of amplifier

Maximum amplification 6×10^6



supply voltages and despite tube replacements, and the "drift" due to the previously mentioned uncancelled residue may be made as small as desired. The basic circuit that accomplishes these results will now be discussed.

The Basic Circuit of the Amplifier (Figure 2)

The circuit characteristics set forth in the following discussion depend on calculations which assume operation over the linear portion of the tube characteristics. Such calculations are valid since the amplifier is actually operated over the essentially linear portion of the tube characteristics. The discussion is valid not only for pentodes, the tubes used, but holds equally well for tetrodes and triodes. The calculations upon which the discussion is based are more complex in the case of tetrodes and pentodes than they are in the case of triodes.

The following symbols will be used:

R_0 is the plate load resistor and has the same value on each side of the amplifier stage.

R_p is the dynamic plate resistance of the tube. The subscripts (1, 2) refer to tubes *VT*1 and *VT*2 and indicate that the tube constants may differ for different tubes.

R_{ps} is the static plate resistance of the tube at a given operating point and is the ratio of static plate voltage to static plate current.

μ is the amplification factor of the tube at the operating voltages used. The subscripts have the meaning already given.

R is the common cathode resistor.

E_1 and E_2 are the input voltages to the stage in the arrow directions specified.

E_3 and E_4 are the output voltages of the stage in the arrow directions specified. Since R_0 is the same for both sides of the stage, $E_3 = -E_4$ is equivalent to $I_1 = -I_2$ in the arrow directions.

Supply voltages have been left out in the interests of simplicity. All of the above voltages and currents are signal components of voltage and current only.

If, in this circuit, R has the value

$$R \geqq 10(R_0+R_p)/\mu$$

in which μ is the smallest of μ_1 and μ_2 and R_p is the largest of R_{p1} and R_{p2}, a condition on R that is easily fulfilled, the circuit has the following properties:

1. If the circuit of figure 2 is replaced by the usual equivalent circuit for the vacuum tube, the cathode resistor R is replaced by an effective resistance which has the approximate value of $2R\mu$.

2. The property stated above makes the plate current of both tubes practically independent of variations in plate-supply voltage, the degree of dependence depending on the magnitude of R. This dependence may be made arbitrarily small, within practical limits, by making R arbitrarily large.

3. The property of "1" also renders the plate current of both tubes independent of variations in the dynamic plate resistance of the tubes. This property renders the operating voltages of the circuit independent of tube aging and tube replacement.

4. A single-ended input voltage E_1, $E_2=0$, applied to one side of the amplifier stage will produce essentially balanced, push-pull output voltages. The total output voltage, E_3-E_4, will be the same as that produced by an input voltage, $(E_1'-E_2')$, applied from grid-to-grid, where $(E_1'-E_2')$ is equal to the voltage E_1 applied from one grid to ground.

This feature is the phase-inverting property of the circuit and has already been discussed for triodes by Goldberg.[2] This phase-inverting property of the circuit enables the amplifier to produce the same output voltage for a given input voltage irrespective of the manner in which the input voltage is applied to the input circuit of the amplifier.

5. Essentially balanced, push-pull output voltages are produced by the stage regardless of unbalances in input voltages, or differences in the characteristics of the component tubes. (A calculation made for a typical circuit to which balanced, push-pull input voltages are applied but in which the plate resistances of the component tubes differ by 10 per cent shows that the output voltages differ by only 0.1 per cent when $R=7(R_0+R_p)/\mu$, a value of R less than that recommended.)

6. The final and one of the most important properties of the circuit is that amplification of balanced push-pull voltages is not affected by the introduction of the cathode resistor, R, since the plate and screen currents due to such voltages cancel in the common cathode lead. The amplifier, therefore, provides full amplification for desired signals but is relatively insensitive to "in-phase" input voltages and to undesirable variations within the amplifier itself.

Before going on to the operation and adjustment of the amplifier, yet another portion of the design must be discussed. At very high amplifications, a "drift" in the output voltage will appear due to the combined effect of heater-voltage-drop with time, and differences in the heater-voltage-emission characteristics of the component tubes in the first two stages. The circuit just discussed does not minimize such variations except for the partial cancellation provided by the push-pull construction of the amplifier. Small, quick, random variations in heater voltage are smoothed over by the inherent time lag between changes in heater voltage and corresponding changes in emission in heater-type tubes. Slow, steady changes in heater voltage, however, will produce changes in emission and will cause drift if the emission changes are different in the tube components of each of the first two stages of the amplifier. This effect may be reduced to a negligible quantity by providing a portion of the grid and screen voltages of the first two stages from the heater-voltage supply in such a way that any change in the heater voltage, will change the emission and the grid and screen voltages in such an antagonistic manner so as to keep the steady-state plate current constant. It has been found that an adjustment of the circuit that will do this for any one type 38 tube in the first two stages, will do it sufficiently well for any other type 38 tube that may be used to replace the original so as to keep the drift due to this cause within a tolerable minimum at maximum amplification. The paper will now discuss the operation and adjustment of the amplifier.

2. For numbered reference, see list at end of paper.

Operation and Adjustment

It is desirable from the standpoint of the proper operation of the amplifier to provide a means of adjusting the static operating voltages in each stage differentially, so that the static plate-to-plate voltage of each stage may be adjusted to zero or very nearly to zero. Such an adjustment provides for the maximum of stability in the amplifier, provides a

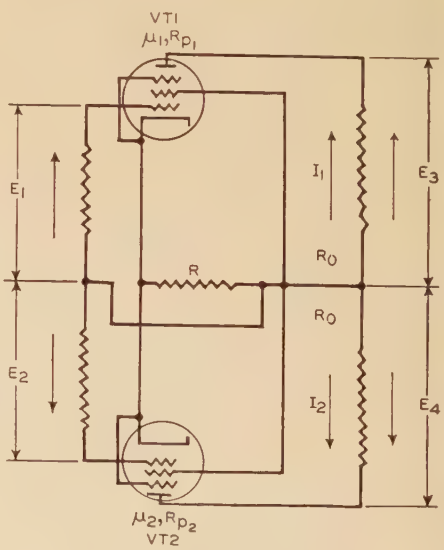


Figure 2. Basic circuit of amplifier

means of controlling the amplification without shifting the operating voltages of stages following the amplification control, and allows the output stage to operate in a balanced condition. This last condition is not only necessary both from the standpoint of efficient operation and battery economy, but also from the standpoint of the necessity of keeping the

cathode-ray-tube spot near the center of the screen with zero input voltage to the amplifier. Since it is sometimes desirable to shift the zero input voltage position of the spot to various other positions on the screen, the static plate-to-plate voltage balancing control of some one stage may be used to unbalance the static output voltage of the amplifier sufficiently to move the spot to the desired position.

In addition to the balancing controls, and a means of varying the voltage amplification, there should be some method for controlling the width of the band of frequencies transmitted by the amplifier, at least at the higher amplifications, so that the inherent amplifier noise may be reduced to considerably less than a microvolt in those cases where the input voltage is very small and the reduction in band width is not objectionable. Finally, there should be some means for quickly and simply checking the condition of the static plate-to-plate voltage balance of each stage.

The scheme for checking such balances is as follows: Plate-to-plate short-circuiting switches are provided in the second and third stages. The closing of such a switch automatically balances the static plate-to-plate voltages applied to the grids of the following stage but does not affect the mean operating voltages of that stage unless the preceding stages are seriously unbalanced, a condition that does not exist in this amplifier unless some portion of the amplifier is defective. These balance indicating controls are provided for the second and third stages and not for the output stage since the static plate-to-plate voltage of the output stage is never more than a few volts (depending on the component tubes) and is not objectionable. The third stage is balanced by closing the second-stage plate-to-plate short-circuiting switch and adjusting the balance control in the third-stage plate circuit until alternate opening and closing of the third-stage plate-to-plate short-circuiting switch does not produce motion of the spot on the cathode-ray-tube screen. This condition occurs only when the static plate-to-plate voltage of the third stage is zero, the condition of balance. Adjustment of the second stage is accomplished in a similar manner. The first stage balance is set with the aid of a voltmeter whenever tubes are replaced in that stage, and does not need readjustment as long as the same tubes are used. In normal use of the amplifier, the second stage is not adjusted to balance, the balancing circuit in this case acting as a centering device, coarse and fine controls being provided for ease in adjustment.

Circuit Description

The input to the amplifier, as illustrated in figure 1, is high-impedance grid-to-grid, the grid-leak resistors providing push-pull input to the first stage. An input that is unbalanced to ground may be connected from either grid to ground, the remaining grid being grounded in this case. As has been stated, the output voltage from the amplifier for a given input voltage is the same whether it be applied from grid to grid or from one grid to ground. For this reason, calibration voltages may be supplied by the injection of known direct voltages into the grid circuit of one tube of the input stage. These voltages may be varied from 2×10^{-6} to 5×10^{-2} volts. The 100,000-ohm potentiometer, P_2, is used to balance the static plate-to-plate voltage of the first stage. Since this control can adjust for a static plate-to-plate voltage not greater than one volt, the tubes in this stage must be matched to the extent that the *IR* drops in their plate load resistors differ by not more than one volt. Tubes which will match in an ordinary tube checker will meet this requirement in about 50 per cent of the cases, although the operating voltages in the amplifier differ considerably from the rated operating voltages of the tubes as provided by the tube checker. The voltage amplification of the first stage may be changed from 15 to 1.25 by shunting a 75,000-ohm resistor, R_2, figure 1, from plate to plate. This reduction makes the over-all gain of the amplifier about 500,000 maximum, as compared to 6,000,000 with the shunt removed. This lower range is desirable when the maximum available voltage amplification is not needed since the lower amplification of the first stage will minimize unbalances in the second stage due to d-c polarization voltages which may occur at the electrode contacts with the biologic specimen being studied.

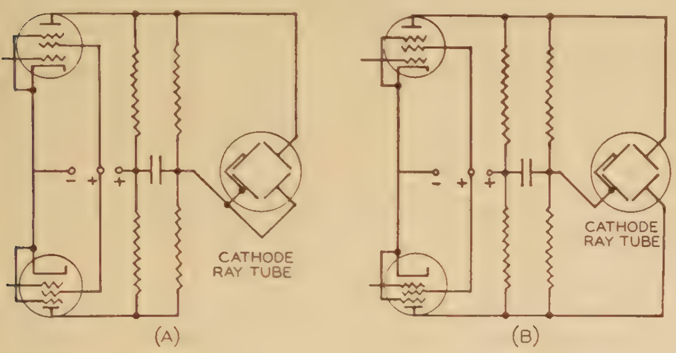


Figure 3. Suggested schemes for connecting the amplifier to ordinary cathode-ray tubes with internal connections between two plates and the anode

Figure 4. Response of amplifier to 100-microvolt calibration voltage applied by manually depressing calibrator key

The dashes are a portion of the timing record and represent 0.04-second intervals

Tube matching on a tube checker is sufficient for tubes in the second stage. The balance control, which is also the centering control, is also used to counteract any effect of steady input voltages brought about by electrode polarization, etc. This control circuit injects a continuously variable push-pull voltage into the second-stage plate circuit which may be reversed by means of the reversing switch. The one-megohm variable resistor, P_3, shunted between the plates of the second stage provides a continuously variable means of controlling the magnitude of the amplification. Reduction in band width is obtained by means of three different shunting capacitors across the control and are effective only when the gain control is near maximum.

There are two means for bringing about static balance in the third stage and these are of sufficient range so that unmatched tubes, taken at random from the dealer's shelves, may be used for this stage. A coarse means is provided by the six-ohm variable resistance, P_4, and a reversing switch, which provides a variable resistance in the heater circuit of either tube at will. This control cannot be used for fine adjustments because of the time lag in the heater-voltage-cathode-emission characteristic. It is used only when discharging batteries have brought about a marked drop in heater voltage or when tubes are replaced in the stage. Fine adjustment is accomplished with the 10,000-ohm potentiometer, P_5, in the plate circuit of the third stage.

Tubes matched in a tube checker are sufficiently alike in their characteristics so that they will work satisfactorily in the output stage. Balancing is unnecessary since the static output voltage is never more than a few volts with such tubes, and has a negligible effect on the position of the cathode-ray-tube spot. Grid bias for the output stage is partially variable by means of the variable resistor, P_6, so that it may be adjusted to the optimum value under conditions of actual operation.

The output connections of the amplifier as shown in figure 1, are intended for a cathode-ray tube which has separate connections to all deflecting plates. The mid-terminal is connected to the anode, and the two outer connections to a pair of plates of the cathode-ray tube. Figure 3*A* and *B*, illustrate possible connection schemes which may be used with cathode-ray tubes possessing internal connections between two deflecting plates and the anode. The connection, *A*, makes use of only half of the output voltage of the amplifier, and for this reason, the plate-supply voltage of the output stage must be increased over that indicated in figure 1, so that half of the undistorted voltage output will be sufficient to give full deflection. The scheme, *B*, applies push-pull voltages to both sets of deflecting plates and results in a deflection proportional to 0.707 of the output voltage of the amplifier. The direction of deflection in this case is along a line making an angle of 45 degrees with the axis of either set of plates.

Constructional Details

The amplifier is built in two units to minimize the effects of stray coupling. The first unit, which is well shielded to prevent pickup, contains the first two stages of the amplifier and all of its associated batteries with the exception of the six-volt storage battery supplying the heater voltage. Small 22.5-volt *C* batteries are used to supply plate and screen voltages with a total drain of less than a milliampere. Tubes are packed in absorbent cotton, shielded, and mounted in suspension mounts by means of rubber bands for the purpose of minimizing microphonic disturbances. Shielded cables connect to the calibration key and to the unit containing the last two stages. The maximum voltage amplification of the first two stages is 350.

Figure 5. Record of one cycle of the injury action potential from the surface of a tortoise heart

The dashes represent 0.04-second intervals. The total elapsed time for each cycle is 4.3 seconds. This record illustrates one type of low-frequency phenomena handled by the amplifier

The last two stages, which have a voltage amplification of approximately 17,000, are housed in a small commercial-type amplifier chassis. Connections to batteries are by a multiconductor cable. Light-duty 45-volt batteries supply the 225 volts of plate-supply batteries needed for the last two stages. Circuit arrangements are such that the actual supply voltages to stages one to four are 22.5, 57, 67.5, and 225, a total of 372 volts, although the total plate battery supply is only 294 volts. Proper bias voltages are obtained for each stage, despite the large cathode resistors employed, by proper circuit design.

Performance

In actual operation, a warming-up period of about 15 minutes is required to secure stability at the higher amplifications. After the amplifier has reached steady-state conditions, minor adjustments to the static balance may be necessary but can be made in no more than a minute or two if necessary. During use, after initial adjustments have been made, only the amplification, centering, and calibration controls need be used.

The amplifier described has been in constant use for a year and a half and has given extremely satisfactory results. In all this time, there has been no necessity for battery or tube changes and the aging of the batteries used with the amplifier has in no way impaired its performance. The amplifier has proved itself to be very dependable and has justified its design in every way. That the performance of the amplifier is not fortuitous is demonstrated by the fact that another such amplifier has been built and been in use for the last year and it has performed just as dependably as the original.

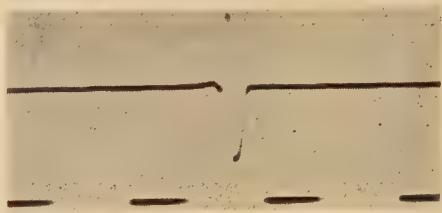


Figure 6. Record of the action potential produced during the contraction of a frog's gastrocnemius muscle

The voltage amplification used for this record was approximately 450,000. The dashes represent 0.04-second intervals

This paper, therefore, has described a d-c amplifier whose over-all voltage amplification is comparable to those obtained in resistance-capacitance-coupled amplifiers and is limited only by the unavoidable noise level of the tubes in the first stage.

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Transactions

Preprint of Papers and Discussions Comprising Pages 65–128 of the 1940 Volume

Capacitor Relay Timing in Industrial Control

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Synopsis: The trend toward electrical means of providing timing for motor control is evidenced in the use of capacitor-timed relays and contactors. Though employed for some time in welding applications, the advent of capacitor timing in the motor control field is fairly recent. The general analytical considerations are presented, followed by a discussion of the component parts of the timer. Some attention is paid to limitations, particularly in regard to the effect of line voltage fluctuations.

THE provision of simple, reliable, and inexpensive timing means has been a perennial problem with industrial-control engineers. Many different physical phenomena involving time have been made to serve as the basis of timing systems, with varying success. During this process of development, the accepted method of motor acceleration has passed through an earlier stage in which current- or voltage-responsive methods were in favor, to that of more recent practice which consists of carrying out the various steps of armature and field acceleration in accordance with a definite time sequence. Thus, the development of timing methods has been accelerated by their increasing importance in the field of motor control.

Moreover, the recent rapid development of the resistance-welding field has presented to control engineers timing problems of a very exacting nature, and has resulted in refinement of existing methods and the introduction of new ones. These methods are now being carried over into the older domains of industrial control with beneficial results.

The earlier forms of timing employed in motor acceleration were mostly of mechanical type, such as dashpot and clockwork mechanisms. More recently, however, the trend has been toward what may be termed electrical means, based on the storage of energy in self-inductance elements or in capacitors. The former type has been in successful use for a number of years (in the so-called "inductive time limit" or "magnetic time" controllers).[1]

On the other hand, though long viewed as a hopeful possibility, capacitor timers have presented many difficult problems only recently overcome in such a manner as to make their use entirely practical. Recent improvements in electrolytic capacitors, particularly those of the etched-plate and fabricated-plate types, have aided in solving such problems, and at least one manufacturer of industrial control is already employing capacitor timing quite extensively both in resistance welding[2] and in motor control. It is the purpose of this paper to outline the general principles of this type of control, and to describe some typical applications.

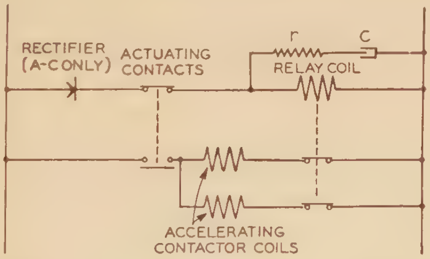

Figure 1. A circuit for timing two accelerating contactors employing a capacitor timing relay having two independent armatures

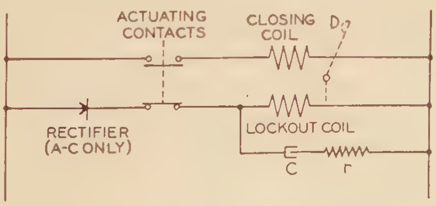

Figure 2. Capacitor timing circuit suitable for lockout-type accelerating contactor

Typical Capacitor-Timing Circuit

The earliest capacitor timers in general use were those employing paper capacitors of about one-microfarad capacity in conjunction with rheostat having resistance on the order of one megohm. This timing combination was connected in the grid circuit of a vacuum or gas triode which acted as an amplifier and controlled power switching apparatus of either magnetic or electronic type. Such "capacitor-resistor" timers have been widely used in resistance-welding control and elsewhere.

However, for motor-acceleration timing and many other purposes this arrangement is too complicated to be practical, particularly in the typical case where two or more successive timing periods are involved. The necessity for periodic replacement of tubes has been an additional barrier.

In an attempt to overcome these disadvantages, it has been found possible to simplify the capacitor-resistor idea by the employment of capacitors of much larger capacity (on the order of 25 microfarads) making possible the elimination of the amplifying tube. Also, to meet the need for multiple timing, relays have been developed which provide two or more independently adjustable time periods with a single magnetic structure.

The circuit used for this purpose is extremely simple (figure 1). The timing-relay coil is connected in parallel with a capacitor and has two or more independent armatures which are connected in circuit with coils of accelerating contactors. When the actuating contacts are in the position shown, the capacitor is charged and the relay coil is energized. When the actuating contacts are moved into the other position, the coil and capacitor are cut off from the line, and the relay armatures drop in turn after definite time intervals.

Variations of this simple scheme are obviously possible, such as connection of the relay coil in series with the capacitor in a charging circuit. However, the ap-

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1. For all numbered references, see list at end of paper.

parently inevitable, though small, leakage current in electrolytic capacitors prevents ultimate reduction of current to zero in a charging circuit and makes the shunt discharge arrangement shown the more desirable.

It is also possible to use the delayed-release magnet as a lockout or restraining

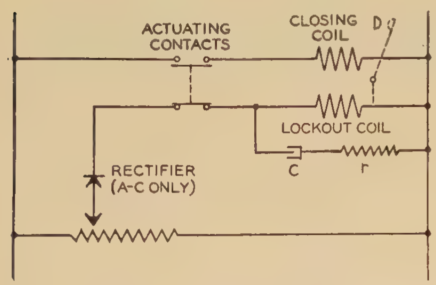

Figure 3. Same as figure 2 except for adjustment of timing by varying initial ampere-turns

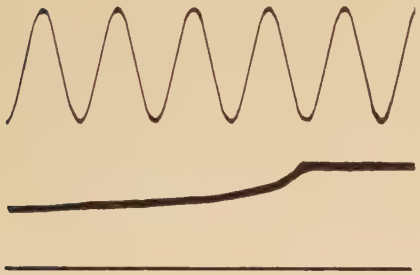

Figure 4. Variation of coil current at start of timing period

Upper trace is 60-cycle timing wave. Ohms in resistor *r* equal twice ohms in coil

magnet in relays or contactors having a separate closing coil (figure 2).

This arrangement has the distinct advantage that the delayed-release coil can be designed for most efficient delay exclusively, whereas in the scheme of figure 1 this magnet has also to perform the function of pulling in the relay. Both figures 1 and 2 are being used, but the former more extensively because it permits using a single standardized timing relay with a wide variety of contactors of standard type, both direct current and alternating current. When used on alternating current it is merely necessary to add the half-wave rectifier unit indicated on the figures.

Nature of Timing Transients

The capacitor-relay timer differs from the electronic timers in that the discharge path contains self-inductance as well as resistance. It is shown further on in this paper that the former may be neglected in most practical cases, but for purposes of analysis it is necessary to take self-inductance into account initially. This involves the well-known transient relationships in a series L-C-R circuit[3] which are repeated here only insofar as they clarify the points under discussion.

Let

L = self-inductance of coil, henries
R = resistance of coil (plus external resistor if used), ohms
C = capacity, farads
i = transient current, amperes
i_0 = initial transient current, amperes
ϵ = 2.718
t = time, seconds
A_1 and A_2 = integration constants
$B = \sqrt{R^2 - 4L/C}$
E = line volts = initial volts on charged capacitor
n = turns in coil
m = ampere-turns at which magnet releases armature

The fundamental equation is

$$L\frac{d^2i}{dt^2} + R\frac{di}{dt} + \frac{i}{C} = 0 \qquad (1)$$

and is applicable to either charging or discharging conditions. For the present purpose, however, the discharging condition is the one of practical importance and is the only one considered here. The general solution of equation 1 is

$$i = A_1\epsilon^{\frac{-R+B}{2L}t} + A_2\epsilon^{\frac{-R-B}{2L}t} \qquad (2)$$

Applying the terminal conditions $i = 0$, capacitor volts $= E$, when $t = 0$, to equation 2 results in the equation:

$$i = \frac{E}{B}\left[\epsilon^{\frac{-R+B}{2L}t} - \epsilon^{\frac{-R-B}{2L}t}\right] \qquad (3)$$

The value of B in the exponential permits three distinct conditions:

$$R^2 < \frac{4L}{C}, \quad R^2 = \frac{4L}{C}, \quad R^2 > \frac{4L}{C}$$

As is well known, the first of these conditions corresponds to an oscillatory discharge. Such a discharge is useless for the purpose here considered, although it does have practical applications in magnet operation in the so-called *impulse* operation of magnetic contactors.[4]

Delayed-release magnets of the type here discussed must necessarily have coils of high impedance, being wound with many turns of fine wire. As the turns are increased by reducing the size of wire in any coil of given dimensions, there is a much more rapid increase in the quantity R^2 than in L, since L varies as n^2, while R^2 varies as n^4. The lower space factor of finer wire accentuates this condition. Furthermore, the values of capacity involved are large (on the order of 25 microfarads).

From the above facts it follows that the normal condition in the present application is that $R^2 > 4L/C$. In practical cases of coils and capacitors used for timing of this type, R^2 varies from 2 to 2.5 times $4L/C$. Calculation of timing under such conditions which neglect L altogether are found to give results within the limits of accuracy established by the normal manufacturing variations of the circuit components.

Where L is neglected, equation 3 reduces to:

$$i = i_0\epsilon^{\frac{-t}{CR}} = \frac{E}{R}\epsilon^{\frac{-t}{CR}} \qquad (4)$$

which is solved for t as follows:

$$t = CR \log_\epsilon \frac{i_0}{i} \qquad (5)$$

These are the equations applicable to the simple capacitor-resistor timer of discharge type.

In a practical capacitor-relay timer, the timing magnet will release at some definite value of ampere-turns, which can be introduced into equation 5 by writing it:

$$t = CR \log_\epsilon \frac{ni_0}{ni} \qquad (6)$$

Methods of Adjustment

Questions of relay and coil design and selection of circuit constants are to some extent dependent on the method adopted for providing adjustment of timing. The available methods are implicitly expressed in equation 6.

Type 1—Adjustment of Capacity. Practicability of this method suffers from the

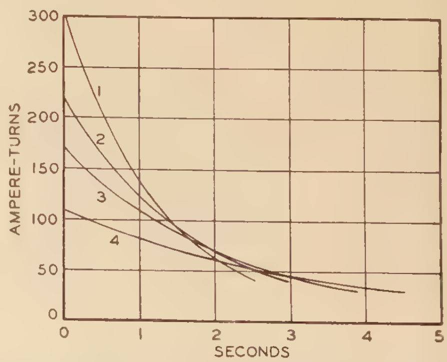

Figure 5. Ampere-turns versus time for different values of external resistance r

Curve 1—r = 30,000 ohms
Curve 2—r = 50,000 ohms
Curve 3—r = 70,000 ohms
Curve 4—r = 122,000 ohms
Coil resistance = 20,000 ohms

lack of adjustable capacitors of large capacity. It is, however, being used on resistance welding timers where the limited timing range makes stepped adjustment of capacity (by a fan switch) permissible. Adjustment by capacity has the advantage that it permits the use of an insulated dial with definitely calibrated points.

Type 2—Adjustment of Resistance. This method is not practicable because there is no way to adjust the resistance of the relay coil.

Type 3—Adjustment of Initial Ampere-Turns. This may be done by varying the voltage to which the capacitor is charged. Without unreasonable circuit complication it is only applicable where the delayed-release magnet has only a restraining function, as in figure 2. Figure 3 shows a practical circuit, which, however, is not in use because of the greater simplicity of other methods.

Type 4—Adjustment of Dropping Ampere-Turns. To accomplish this simplest method of adjustment it is only necessary to provide for changing the magnetic gap of the relay armature when in closed position. It is applicable where the delayed-release magnet has both a pickup and restraining function (figure 1) as well as where it has a restraining function only (figure 2).

Factors Affecting Timing

In all cases it is desirable to use a resistor unit r in series with the capacitor. The ohmic value of this resistor may be anything from a minimum value which is recommended for protecting the capacitor against surges, to a much higher value which may be desirable to obtain maximum timing efficiency. Whether the latter may be used depends upon whether it is permissible to take appreciable time to recharge the capacitor between operations. In some cases, additional actuating contacts are used to commutate this

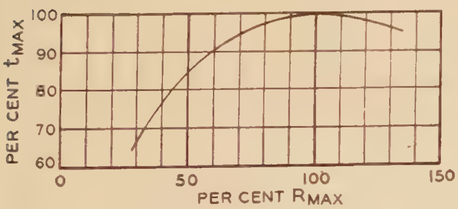

Figure 6. Plot of equation 10

resistor so that its ohmic value is low for the charging condition and high for the discharging condition.

Referring to figure 1, it will be seen that the ampere-turns in the relay coil, before the actuating contact is opened, are simply determined by the coil characteristics and the line voltage. When the actuating contact is opened, the current in the relay coil drops in a transient period of negligible duration to a value depending upon the initial charge on the capacitor and the resistance in circuit, figure 4. Thereafter the current varies substantially in accordance with equation 4.

Where the magnet has a pickup as well as a holding function, the coil design is determined by the former. Where the function is holding only, on the other hand, the coil is wound with the finest wire which can be wound economically. Figure 5 is a set of curves plotted in accordance with equation 4, for a particular coil and capacitor and for various values of R. These curves are plotted in ampere-turns rather than amperes because

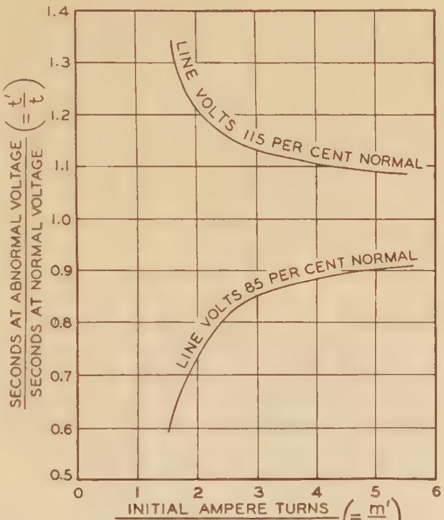

Figure 7. Effect of voltage variation on timing, expressed as a function of the ratio of initial to final ampere-turns

the pickup and dropping characteristics of relays are so expressed.

To determine the value of R which results in maximum timing, the form of equation 6 may be changed to

$$t = CR \log_\epsilon \frac{En}{mR} \tag{7}$$

wherein m is the dropping ampere-turns.

Differentiating equation 7, and equating to zero to find R for maximum t, results in

$$R_{\max} = \frac{En}{m\epsilon} \tag{8}$$

$$t_{\max} = CR_{\max} \tag{9}$$

There are two practical considerations

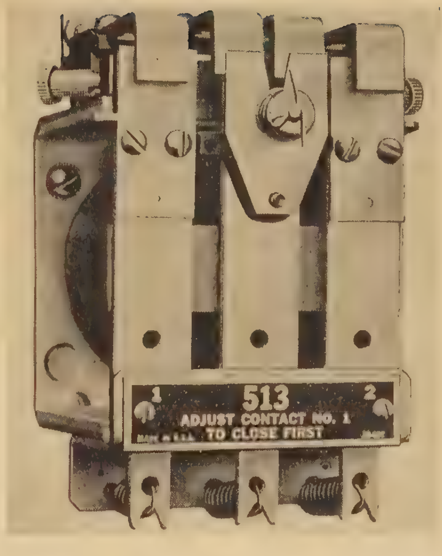

Figure 8. The relay for armature acceleration has two (outer) armatures for timing, and a third (center) armature for insuring correct operating sequence

which make it undesirable to use the full value of total resistance indicated by equation 8:

1. Variation of coil ampere-turns near the point of relay armature release may be so gradual that small changes in release ampere-turns cause appreciable changes in timing.

2. Effect of line-voltage fluctuations on the timing is excessive. This factor is discussed in the next section of this paper.

Combining equations 7, 8, and 9 results in the following equation which expresses the effect on the timing of using a value of R which differs from $R_{\max}$:

$$\frac{t}{t_{\max}} = \frac{R}{R_{\max}} \log_\epsilon \frac{R_{\max}\epsilon}{R} \tag{10}$$

This equation is plotted in figure 6 and shows that reduction of R to 50 per cent of $R_{\max}$ only results in 15 per cent reduction in timing. This value of R corresponds approximately to that used in actual practice. Where the timing adjustment is by variation of closed magnetic gap (type 4) the value of R is important not only for its effect in increasing the time periods available with given apparatus, but also because the flatness of the timing curve determines the range of timing adjustment available. Thus with curve 3 of figure 5 the range of timing from zero to four seconds is obtainable by changing the dropping ampere-turns from 170 to 35, whereas to obtain the same range of adjustment under the conditions of curve 1, figure 5, may be seen to require a much wider adjustment of dropping ampere-turns, which may not be obtainable in practice.

Effect of Line-Voltage Fluctuations

Fluctuation in line voltage constitutes the most serious adverse factor in this timing method. It is desirable to show the extent of its effect and how the latter may be minimized.

Let

m = dropping ampere-turns, as above
m' = initial ampere-turns, at nominal line volts
k = ratio of actual to nominal line volts
t and t' = timing at nominal and actual line volts, respectively

Then equation 6 may be written:

$$t = CR \log_\epsilon \frac{m'}{m} \tag{11}$$

and, since initial ampere-turns is proportional to line volts,

$$t' = CR \log_\epsilon \frac{km'}{m}$$

or

$$\frac{t'}{t} = \frac{\log_\epsilon \frac{km'}{m}}{\log_\epsilon \frac{m'}{m}} \tag{12}$$

In figure 7, equation 12 is plotted for $k = 0.85$ and 1.15. These curves clearly show that low values of m'/m accentuate the effect of line voltage fluctuations. If $R = R_{max}$ is used in order to obtain maximum timing, the initial ampere-turns are, using equation 8,

$$m' = \frac{En}{R_{max}} = m\epsilon \text{ or}$$

$$\frac{m'}{m} = \epsilon = 2.718$$

It was stated in the preceding section that use of the full value of R_{max} leads to excessive sensitivity to line voltage fluctuations. Reference to figure 7 shows a variation of roughly ±15 per cent in time for a ±15 per cent voltage variation, which might be permissible. But in the case of a type 4 adjustment, timing is reduced by increasing the dropping ampere-turns; that is, by increasing m in equation 11, with corresponding decrease in m'/m. Figure 7 shows that decreases in m'/m by this method below 2.718 over any appreciable range would result in very excessive voltage sensitivity over the lower end of the range.

On the other hand, by using considerably lower values of R, such as $R_{max}/2$, this tendency is greatly reduced since, for maximum timing, $m'/m = 5.43$. An inspection of figure 7 shows that the permissible range of variation of m'/m in this case is considerably greater than when $R = R_{max}$. Experience has shown this to be an acceptable compromise value.

Typical Controller

Figure 8 illustrates a capacitor-timed relay generally used for armature acceleration. The outside armatures are provided with normally closed contacts and individual closed magnetic gap adjustments for timing. A center armature carries a normally open contact and a fixed closed magnetic gap. Figure 9 shows a similar relay with two independently timed armatures carrying normally open contacts. This relay finds particular use in field acceleration.

A typical automatic d-c motor control with both armature and field acceleration is shown in figure 10. Figure 11 is the elementary diagram for this control. For the sake of simplicity, the overload relays, dynamic braking contactors, and field and voltage failure relays have been omitted from this diagram.

Two forward and two reverse contactors are shown. Armature acceleration contactors $1A$ and $2A$ are controlled by a capacitor-timed relay, CT, of the type illustrated in figure 8. Two capacitors are supplied with this timing relay in reversing controllers of this type, for reasons outlined below. The capacitors are designated CAP.-1 and CAP.-2 on the diagram and are connected in the circuit with normally closed auxiliary contacts on the reversing contactors, as indicated. A capacitor relay, FA, identical with that shown in figure 9, provides field acceleration.

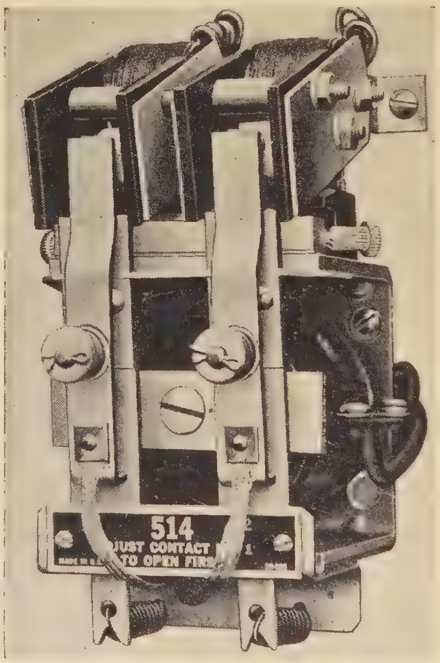

Figure 9. The relay for field acceleration has two independently timed armatures

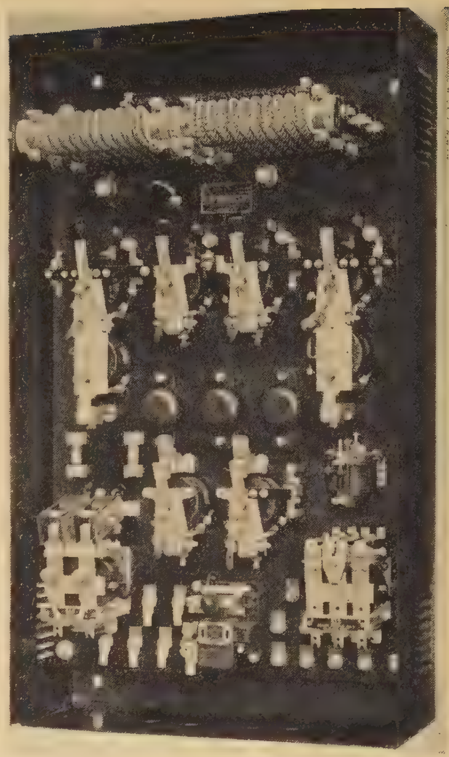

Figure 10. A full-reverse nonplugging, dynamic-braking d-c motor control with three steps of armature and two steps of field acceleration

Operation of this control is, briefly, as follows. With voltage on lines L_1 and L_2, relay CT picks up, closing contact CT-$N.O.$ and opening contacts CT_1-$N.C.$ and CT_2-$N.C.$ Capacitors, CAP.-1, CAP.-2, and CAP.-3 are charged through their respective external resistors. Relay FA also operates, closing contacts FA_1 and FA_2.

When the "forward" push button is closed contactors $1F$ and $2F$ close, connecting the motor armature to the line through the two steps of starting resistance. Contactor $1F$, in closing, opens an auxiliary contact $1F$-$N.C.$ which disconnects the coil of the timing relay CT from the line and allows CAP.-2 to discharge through it. This initiates timing on CT, and contacts $CT1$-$N.C.$ and $CT2$-$N.C.$ close successively at preset timing intervals to energize $1A$ and $2A$ respectively, which in turn short-circuit the two steps of starting resistance. During this time, contact CT-$N.O.$ has opened and the main contactors $1F$ and $2F$ are maintained through the interlocking resistance. Contactors $1F$ and $2F$ are picked up only when contact CT-$N.O.$ is closed. The latter is operated by the center relay armature which is provided

with a larger open magnetic gap than the armatures carrying contacts *CT1-N.C.* and *CT2-N.C.* This assures that the latter two contacts are opened before contactors *1F* and *2F* close. Contactors *1A* and *2A* cannot therefore close at the same time as *1F* and *2F* and connect the motor armature directly across the line.

When contactor *2A* closes, it operates an auxiliary contact *2A-N.C.* which disconnects relay *FA* from the line and allows *CAP.-3* to discharge through the coil. Contacts *FA1* and *FA2* open successively at preset intervals inserting resistance in series with the motor shunt field. The rheostat permits manual control of the motor speed.

As shown on the diagram, two capacitors are used in conjunction with the relay coil *CT*. While operating in the forward direction *CAP.-2* discharges through coil *CT* to provide timing. On reversal, the auxiliary contact *2R-N.C.* opens and allows *CAP.-1* to discharge through coil *CT*. An alternate circuit utilizing a single capacitor is designated by the broken line on the diagram. Because of the series resistor, a definite time interval is required to charge the capacitor to line voltage. When the "reverse" button is pressed immediately after the motor has stopped from "forward" operation, sufficient time might not be available for a complete charge of the single capacitor. This would result in shorter timing of contactors *1A* and *2A*, and a too rapid acceleration of the motor. To protect against this possibility, a capacitor is provided for each direction of rotation of the motor. While it is operating in one direction, the capacitor circuit controlling timing in the reverse direction remains across the line and is charged to full line voltage.

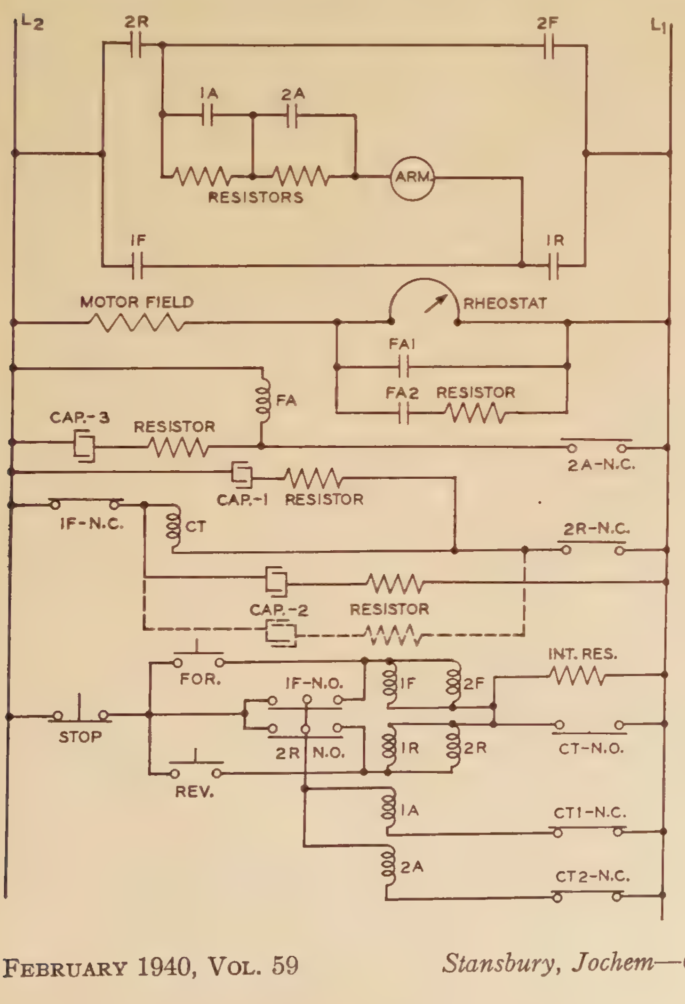

Figure 11. An elementary diagram of connections for the controller illustrated in figure 10

Conclusion

Although the development described in the foregoing paper is quite recent, several hundred controllers employing capacitor-relay timing for acceleration are already in successful service in varied applications. The inherent advantages of this method, as compared with earlier methods, appear to justify the belief that it will be used very extensively in the future.

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Thyratron Control Equipment for Resistance Welding, H. L. Palmer. *General Electric Review*, volume 40, May and July 1937.

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Discussion

F. H. Winter (nonmember) and **L. T. Rader** (both of General Electric Company, Schenectady, N. Y.): We agree with Messrs. Stansbury and Jochem that accurate means for obtaining various time intervals is a very important part of industrial-control work; and the use of capacitors for this purpose offers a very flexible and accurate method of control. In applications where dirt may interfere with operation, operators object to small mechanical arrangements such as escapements, dashpots, and motors to obtain time delays. One of the standard devices having no moving parts but using electrical induction is the coil with short-circuited secondary or copper jacket. It has, however, the two limitations of:

1. A maximum time delay drop-out of seven or eight seconds.
2. It does not lend itself to easy adjustment during operation.

Therefore, as stated by the authors, the comparatively recent reduction in cost of manufacture and decrease in sizes of capacitors, as well as the demand for longer time intervals and more flexible control, has intensified their application. In circuits using no electronic devices we have obtained ranges in time from seven cycles to three minutes. The latter figure was obtained on a motor-starter using 600 microfarads at 250 volts.

We should like to show several uses of capacitor circuits other than those presented. These are:

1. Compensation for voltage changes.
2. A high pickup force.
3. A fast pickup and fast drop-out.
4. Time delay pickup.
5. Use of capacitors as interlocks.

Figure 7 in the authors' paper shows the effect on timing of line voltage fluctuation. Where good accuracy is required, we have eliminated this variation in timing with variation in voltage by the use of the circuit shown in figure 1 of this discussion.

A compensating coil is in series with a regulating rheostat across a potentiometer so that its ampere-turns are directly proportional to the line voltage and in opposition to those of the main coil. When the master control switch (*MCS*) is closed, the normally open interlock completes the circuit to the potentiometer connection, thus energizing the compensating coil. Meantime, the second *N.O.* contact on the master control switch has allowed the capacitor to become rapidly charged from the line through only a small limit resistance. The device picks up and opens the *N.C.* interlock, thus inserting the discharge resistance which will give the proper time constant. To start the time-out operation, the master-control-switch contacts are opened, disconnecting the main coil from the 250-volt bus and putting it across the capacity and discharge resistor in series. The compen-

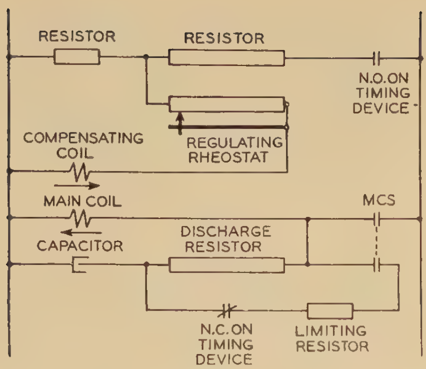

Figure 1

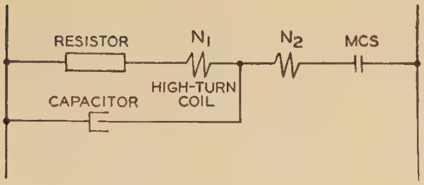

Figure 2

sating coil remains connected to the main bus and for any value of regulating resistance and capacitance, compensation is obtained by proper adjustment of its bucking strength and drop-out spring tension. The only factor which can affect this device adversely is a change in bus voltage which occurs between the time the master-control-switch contact opens the circuit to the main coil and the time the device drops out to the de-energized position. With 100 microfarads capacity, 75,000 ohms discharge resistance, and 16 volts across the compensating circuit, the following time drop-out values for changes in regulating rheostat were obtained:

3,000 ohms—26 seconds
2,250 ohms—22.5 seconds
1,500 ohms—18 seconds
750 ohms—11 seconds
0 ohms—1/5 second

By changing the capacitance, a different range in times may be obtained. Voltage compensation, of course, takes place for any or all the above settings.

The regulating rheostat also gives a means of remote control of time delay when desired. On the above device, when the voltage changed from 150 volts to 280 volts, test results showed a maximum variation of less than one per cent in time drop-out over the complete range.

The authors state that a coil design for a magnet is determined primarily by the pickup value required. However, by using a capacitor, a two-section coil may be designed to give both a high pickup force and an economical holding action. Such a circuit is shown in figure 2.

A high-resistance high-turn coil N_1 is in series with a discharge resistor R, across a capacitor C. N_2 is the second section of the coil consisting of a low number of turns and low resistance, compared to N_1. When *MCS* is closed the N_2, C circuit draws an initially high surge of current, thus producing the required high force through the open or high-reluctance path of the contactor.

By proper design, a high value of ampere-turns, sustained through an ample time, can be obtained in a very small winding space due to the short duration of the current. The major part of the winding space is then available for the N_1 winding which performs the holding function after the magnet has picked up. The discharge resistor shown is used solely to obtain time delay drop-out.

In an application where fast pick-up and fast drop-out of a contactor is desired, a connection as shown in figure 3 may be used.

N_1 and N_2 are both 6,000-turn coils, the latter having a resistance only $1/20$ of that

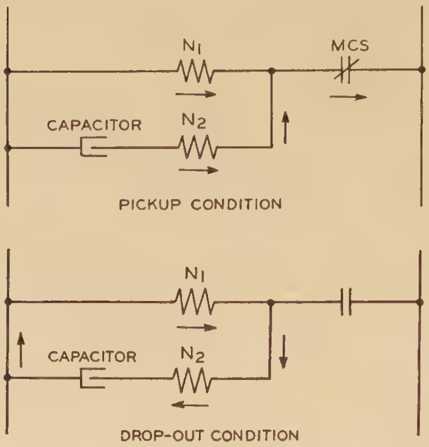

Figure 3

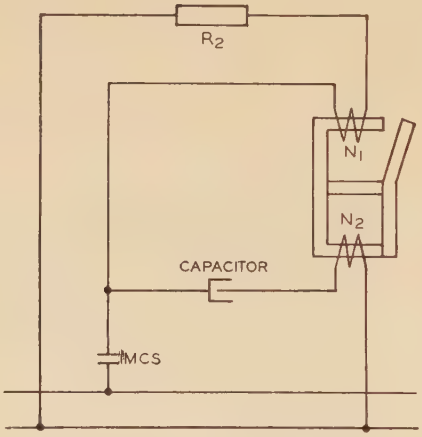

Figure 4

of the former. When contacts *MCS* are closed, the current rush through N_2 aids normal current through N_1 to give a very fast pickup. On drop-out the coils are in opposition so that the capacitor discharges through a circuit of low inductance and fast drop-out. A contactor connected in this manner picked up in three cycles and dropped out in one to 1.5 cycles, whereas, the same contactor with standard coil picked up in seven to eight cycles and dropped out in four to five cycles.

The following circuit shown in figure 4 is very similar to that shown by the authors in their figure 2. We feel, however, that some operating characteristics may be of interest.

With the connection shown, electrolytic capacitors cannot be used if long timing of great accuracy is required due to their leakage characteristics. With proper magnetic reluctance relationship between the top and bottom magnetic circuit, the time of pickup is only slightly affected by voltage changes. With two identical coils of 26,000 turns and 4,200 ohms resistance, and with C equal to 50 microfarads, the following results were obtained:

Volts	Time Pickup (Seconds)
285	3.0
250	2.9
200	2.7
150	2.7
100	2.8

To prevent change of timing with temperature, a resistance R_2 of zero-temperature-coefficient wire is used in series with the pickup coil to consume about 80 per cent of the power of the circuit.

With the following connection (figure 5) electrolytic capacitors can be used and much longer times can be obtained.

With the same coils and capacitance as in figure 4, the following data were obtained:

Volts	Time Pickup (Seconds)
280	14.0
250	14.1
200	14.0

Figure 6 shows a simple connection where a capacitor can be used in place of an interlock which would normally short out a resistance on starting.

When *MCS* is closed, the capacitor acts as an initial by-pass for the current, allowing enough flow to pick up the device. The capacitor, on becoming charged, then acts as an open circuit thus putting the limiting resistance in series with the coil.

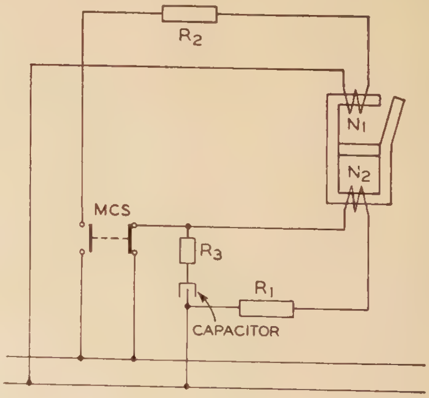

Figure 5

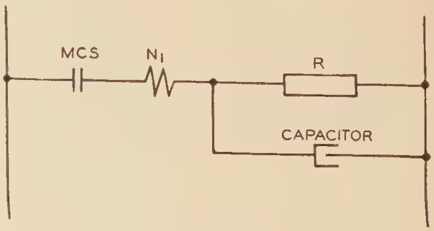

Figure 6

Recent Developments in Telegraph Switching

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IN TIMES when so much thought and attention are given to the streamlined development of modern life, such as aviation, de luxe high-speed trains, airmail, radio, television, sound movies, and other wonders of science, it is quite natural that an industry such as the telegraph should find itself called upon constantly to fill an ever increasing demand for new services or functions created by this world of today. With every new development in modern industry, new needs arise for quick interchange of information—accurate and in written form for permanent record to insure against misunderstanding or forgetfulness. It is these needs which the telegraph, through its system of fast record communications, has been able to anticipate and provide for. Engineering research and developments in telegraphy have fully kept pace with the modern trend, and during the last year or two, there have been brought to conclusion several developments which promise to make the telegraph more necessary than ever to our social and industrial life.

The reperforator switching system of the Western Union is one of these recent products of its engineering laboratories—one that seems destined to change the entire character of the telegraph office, and to advance the art of handling telegraphic communications in a manner fully comparable with other trends of present day life.

It is seldom that new developments embody new principles. Oftener than not, the newest improvements in technology are refinements of what has already gone before. They are what may be considered to be an intelligent fitting together of elements handed to us by our predecessors. Thus the reperforator switching system is but the result of the careful selecting, refining, and fitting together of certain devices and ideas which have come down through the years of telegraph, together with the development of certain new elements which are essential to the success of the system as a whole.

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Relay Offices

By its nature, telegraph business consists of the transmission, in record form, of multitudinous short messages from a large number of sending points to an equally large number of receiving points. Like a railroad system with its variously routed traffic, the telegraph from its earliest days has been able to function economically only through the medium of central transfer points, or relay offices, each of which has direct connection to numerous originating and destination points, and direct wires to one or more other relay points. At these relay offices, as high as 95 per cent of the telegrams relayed are received over printing telegraph circuits and retransmitted over similar circuits, the only exceptions being those messages handled over Morse-operated circuits or by pneumatic tubes connecting with branch offices.

Obviously this system permits handling the maximum amount of business over a minimum number of wires, but it also requires a considerable amount of manual work at the relay offices. To be more specific, the reception of a telegram in a relay office involves the service of a receiving operator who scans the telegram for errors, times it, marks it off on a tally sheet, and releases it. It is then manually or mechanically carried to a distributing center where it is routed to the circuit over which it is to be retransmitted and is manually or mechanically carried to the terminus of that circuit. The transmission out of the relay office requires the services of a transmitting operator. These offices must be adequately staffed with operators, distributing clerks, and supervisory forces, to insure rapid handling, for telegrams must be at their destinations within a few minutes after they have been filed at the originating point. It was with a view of eliminating as many of these manual operations as practicable and replacing them with a single switching operation that the development of reperforator switching was undertaken.

Early Experiments With Storage Devices

During the many years since Morse first invented the telegraph, there have been developed many devices for the automatic transmission and reception of telegraph signals, all intended to increase speed and improve accuracy. However, there has always remained the impracticability of switching signals directly from an incoming to an outgoing circuit, without creating difficulties on the incoming one while waiting for the outgoing one to clear of other business. These waiting times would either cause intolerable congestion of messages on the incoming circuits, or would be seriously wasteful of valuable circuit time, depending on the type of system employed. In order to maintain continuous high-speed operation, it is essential that means be provided for storing the incoming signals without delaying their reception, for moving them immediately from the incoming to the outgoing circuit terminals, and then for retransmitting them on the outgoing circuit just as soon as the latter is clear.

Thus the elements for a successful switching system for commercial telegraph service must include provision for a distant station to transmit into the switching system at any time and at its own convenience, a means of distributing these telegrams at high speed to the transmitting terminals of the proper outgoing circuits at each of which are accumulated, in one storing device, the telegrams for that circuit, and a means for transmitting these accumulated telegrams as fast as the line will accept them. Finally, all of this should be accomplished so efficiently that when circuits are available, an outgoing telegram will be on its way immediately. In addition to these fundamental elements, there must be numerous devices for check purposes to insure that each telegram is handled correctly.

If space and time permitted, it would be interesting to discuss the many different schemes and inventions which previous workers have evolved for a speedier and more efficient handling of telegraphic communications. But such a study would serve principally to demonstrate, once more, that new developments are often but refinements of old ideas, with certain important changes and additions. It would show, for example, that paper tape perforated with holes corresponding to the telegraph code was

used for automatic sending as long ago as in 1846—only two years after completion of the first telegraph line between Washington and Baltimore. It would show that keyboard perforators for preparing such tape were patented over 80 years ago. Automatic recording by a perforated tape was proposed a few years later, while automatic retransmission direct from recorder tape was proposed about 50 years ago. Other inventions which might call for special mention would include various tape perforators controlled by incoming signals, mechanisms for operating type-setting devices from received perforated tape, and printers operating directly from received tape. There also have been arrangements for both printing letters and perforating tape, simultaneously, from received signals.

Numerous inventors have devised mechanical arrangements for receiving and storing signals, such as pin storage devices using plates, drums, disks, or chains and devices employing balls which were dropped in recesses in "letter blocks" that acted as links in a chain. In general, however, mechanical storing transmitters have not met with much commercial success, largely because they are definitely limited in storage capacity. If large capacity is provided in original design, it proves costly and usually entails parts that are too heavy for high-speed operation.

From the foregoing, it will be evident that the fundamental elements of reperforator switching systems are really not new. In fact, the use of reperforators, or some form of storing transmitter, was contemplated by the Western Union in 1912, when its multiplex system was being designed, and code combinations were actually assigned to permit a sending operator to select a distant printer or reperforator, as the case might be.

Reperforators were used to a limited extent in Western Union service about 1925 in connection with transatlantic picture transmission by the Bartlane system, and during 1930 a six-unit reperforator was developed for retransmitting into quotation service branch circuits. This was later modified for five-unit code and was used in inaugurating timed wire service in 1931. The following year perforating attachments were provided for standard multiplex tape printers and teleprinters, so that a perforated tape as well as a printed tape was produced. Although developed primarily for timed wire service, these attachments found many other applications and proved to be especially valuable in relaying large files, such as from the 1932 Olympic games in Los Angeles and the national political conventions.

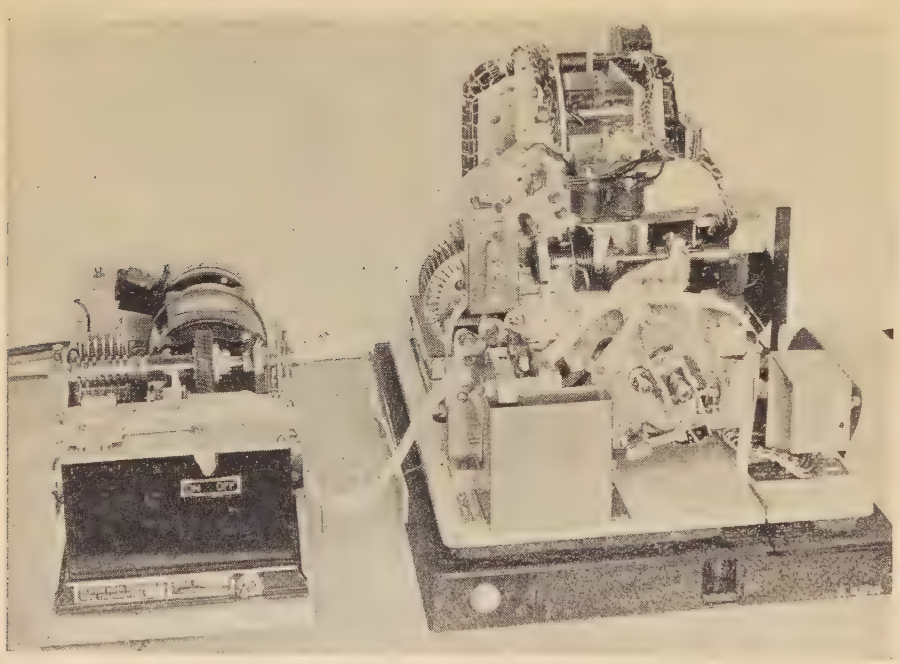

Figure 1. Printer-perforator and transmitter

The first practical attempt by the Western Union to handle regular telegraph traffic by means of automatic reperforation was made in Newark, N. J., in 1933. In this experiment, each telegram, in perforated tape form, was physically transferred from the receiving position to the outgoing circuit, but the results of the trial almost immediately demonstrated that such an arrangement offered no outstanding advantages over existing methods. The difficulties of reading perforated tape at high speed and handling large quantities of short lengths of paper tape, together with the possibility of delaying telegrams in so doing, seemed to offset any advantages that might be gained in other respects.

From the experience gained at Newark, it was evident that automatic recording and retransmission could not be satisfactorily applied to the handling of relay traffic without means for quickly and easily reading the destination of the telegram when it was received in the form of perforated tape, and also some method whereby the tape could be fed continuously through a transmitter associated with the receiving perforator, thus avoiding the accumulation of tape at the receiving position. It was obvious, also, that facilities must be provided for switching the transmitter to various outgoing lines.

Development of Reperforator Switching

The next development, therefore, was the embodiment of these various features into a complete reperforator switching system installed at Fort Worth, Tex., in 1934. This installation in its present form employs perforating printers which print letters on one tape and perforate the code on another, and a switchboard at which the transmitter associated with an incoming message is plugged directly to the outgoing connection. This outgoing connection is not the outgoing circuit itself, but an intraoffice circuit which serves to clear the incoming transmitter and transfer the message to a second storage directly associated with the outgoing circuit. This intraoffice circuit operates at 90 words per minute, as compared with 65 on the incoming circuits, and thus can take up the slack caused by any delay in switching. Transmission on the outgoing circuit is automatic and starts immediately, or at least as soon as the line is cleared of other business. Another important feature is the automatic numbering machine on each outgoing circuit, which inserts consecutive serial numbers in all telegrams sent, so that there is a permanent identification for every message.

Later Improvements in Reperforator Switching

The installation at Fort Worth conclusively demonstrated that the general scheme of operation was correct and

that with the system applied to larger offices, particularly those handling a relatively large proportion of relay traffic, substantial improvement in operation could be effected. It also developed the need of further refinement in certain features. The development of these followed, and in October 1937, the present system was placed in operation in Richmond, Va. Of the numerous features

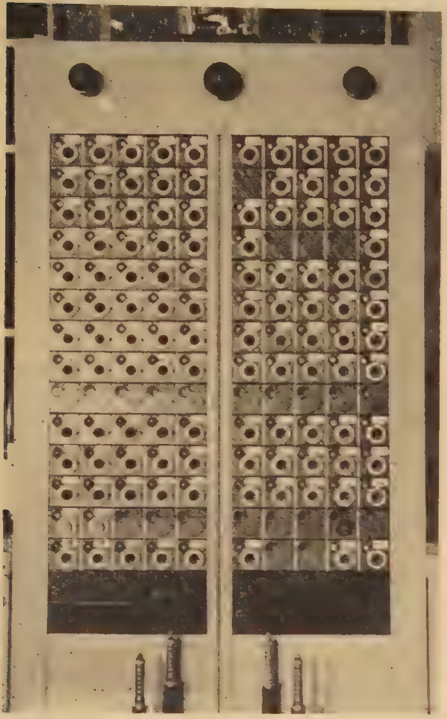

Figure 2. Switchboard

which distinguish this project from the Fort Worth one, most important is the printer perforator, a new printer which simultaneously prints the telegram and punches the code perforations on the same tape, so that the telegram may be read easily by anyone having no knowledge of the telegraph code, and its destination determined as soon as it is received.

Another improvement was the provision for still higher speed on the intraoffice circuits. It was found at Fort Worth that circuits which received continuously for hours, occasionally became congested, due either to gradual accumulation of time employed for switching, or to "waiting time" caused by a needed outgoing circuit being pre-empted by another transmitter. The higher speed necessary to avoid this congestion was obtained through the use of multiwire intraoffice circuits which permitted the transmission of all five impulses of each letter or character simultaneously, instead of consecutively, as in the previous single wire circuits. This arrangement necessitated the development of new high-speed receiving perforators at the outgoing transmitters, but it made possible an intraoffice speed of 125 words per minute. The multiwire circuits were made possible through the development of special jacks and plugs designed to transfer a total of nine circuits simultaneously—five for the code impulses and four for special cord-circuit functions necessary to the switching operations.

Except for a general redesign of the equipment assemblies and arrangements, the only other important novelties incorporated in the Richmond installation were the provision of special switching and storage facilities to permit of differentiation between different classes of business, such for example, as certain rush traffic which requires special handling, deferred rate business which often must be temporarily held in storage, and other traffic which for one reason or another cannot be immediately transmitted to its destination. A more detailed description of the new reperforator switching system follows.

Theory of Operation

In the reperforator switching system which Western Union has installed at Richmond, Va., all printing telegraph circuits terminate in a special switching section. Each of these circuits is, in effect, two circuits, one transmitting and one receiving. All receiving circuits are grouped together in one section of the switching unit, and all transmitting circuits are grouped in another section. Intraoffice circuits between the two sections permit transmission from the receiving section to the transmitting section.

Each receiving circuit terminates in a recording device called a printer-perforator which prints each received character along one edge of a paper tape and simultaneously perforates holes in the tape immediately below the printed character. These holes are printing telegraph code combinations which represent the letter printed above them, and when the tape is passed through a transmitting device they cause that letter to be transmitted. Telegrams may therefore be stored in this paper tape and retransmitted over any other circuit by passing the tape through the proper transmitter (figure 1 shows a printer-perforator and a transmitter).

Each transmitting circuit terminates in a transmitter that is permanently connected to it. Telegrams to be transmitted over these circuits are electrically transferred to them from the receiving positions over intraoffice circuits. These intraoffice circuits are in two parts. One part is formed by a transmitter located immediately adjacent to each printer-perforator in the receiving section, and this transmitter terminates in a cord and plug on the shelf of a switchboard. The other part is formed by a printerless perforator located immediately adjacent to each transmitter in the transmitting section, and it terminates in multipled jacks in all of the switchboards (figure 2 shows a switchboard).

When a telegram is received on a printer-perforator, the perforated tape produced by this device passes through the intraoffice transmitter beside it. The plug of that transmitter is inserted into a selected one of the jacks in the switchboard which completes a circuit to a printerless perforator where the message is again recorded in the form of perforated tape. This perforated tape automatically passes through the line transmitter immediately beside it and the telegram is transmitted to a distant station.

This theoretical description of reperforator switching is, of course, much simpler than the actual operating installation. Many other functions have to be performed in order to make the system practical.

Layout

The switching equipment of all receiving terminals is mounted on double deck-tables in order to concentrate the printer-perforators as closely as possible to the switchboard which serves them, and in order to conserve floor space. Circuits which handle a large number of telegrams are placed in groups of four to each switchboard. In these groups, two printer-perforators, one on the lower shelf and one on the upper, are placed on each side of the switchboard. On more lightly loaded circuits, eight receiving positions are associated with each switchboard. In these cases, two upper and two lower shelf positions are used on each side of the switchboard. A switchboard and its quota of four or eight associated printer-perforators and intraoffice transmitters form a complete receiving terminal unit.

All of these switching units are grouped in two long banks which face each other in such manner as to provide a working aisle where all manual switching functions are performed (figure 3).

Transmitting positions are equipped

with intraoffice automatic perforators, line transmitters, and numbering machines which will be described later. These units are grouped in a separate section of the office on double-deck tables which also face each other to form a working aisle for supervisory and regulating purposes (figure 4).

A third section of the room is formed by manual transmitting and receiving positions similar to those in any other telegraph office (figure 5). Telegrams received over Morse wires or by pneumatic tube or local telephone are transmitted from this section into the switching unit where their handling is identical with the switching operation already described. Telegrams received in the switching unit to be retransmitted over Morse circuits, pneumatic tubes, or local telephone are switched into one of the receiving positions of the manual section where their handling is identical with that in any other telegraph office. There is, however, one difference between these manual positions and those of an ordinary telegraph office. They are not permanently connected to individual circuits, therefore the loads may be concentrated on the fewest possible positions and operators do not have to move from one position to another.

Switching Operations

In the switching section each receiving circuit terminates in a printer-perforator which serves that circuit alone. The printed and perforated tape which comes out of that instrument tends to form a loop between the printer-perforator and the intraoffice transmitter. This loop drops into a glass tank immediately under the printer-perforator and accumulates there until the intraoffice transmitter functions to transfer it across the room to the transmitting positions. The intraoffice transmitter will not operate, however, until a connection has been established through the switchboard. Since this connection is not started until a telegram has been completely received, some accumulation of tape is normal. This accumulation may at times exceed one telegram due to the fact that one switching clerk handles several receiving circuits, but the quantity of unswitched tape on hand is always visible to the clerks and supervisors. Any accumulation of tape which will require more than a minute or two for intraoffice transmission is given continuous attention by the clerk until it has been eliminated.

Before a tape can be switched, it is necessary for the clerk to ascertain its destination and select the switchboard jack connected to the proper transmitting circuit. The printed characters on the tape facilitate this operation. The destination usually appears in the tape about eight inches from the beginning and is readily visible to the clerk.

After noting the destination, the clerk picks up the plug associated with that transmitter and inserts it in the jack of the switchboard which serves the desired transmitting circuit. This operation completes the clerk's work on that particular telegram and she is free to proceed to another circuit.

It is essential that this manually performed portion of the switching operation be completed on the first attempt by the clerk with no waiting. It must be possible for her to insert plugs into jacks whenever that operation is most convenient, and leave all subsequent operations to the functioning of purely automatic equipment. There are frequent occasions when two or more transmitters will have need for the same intraoffice circuit simultaneously, therefore there must be a plurality of jacks in each switchboard which serve the same intraoffice circuit, and each intraoffice circuit must be multipled to all switchboards.

Circuit Allotter

In order that plugs may be inserted simultaneously in these multipled jacks without interrupting one another, a device known as a circuit allotter is used. When a plug is inserted in a jack of the switchboard only a potential connection is established. A plurality of simultaneous potential connections to the same intraoffice circuit are converted one at a time into actual connections through the action of the circuit allotter. This allotter breaks the existing connection at the end of each message and establishes an actual connection from one of the potential connections, repeating this operation until there are no more potential connections.

The circuit allotter is caused to function at the end of each telegram by a special signal which is transmitted by the station which transmits the telegram into the Richmond office. This signal is two periods and one space. It is essential that intraoffice connections be broken at the end of each telegram in order that each telegram may be individually routed over that circuit which will give it the most direct path to its destination. It is the exception rather than the rule that two consecutive telegrams received over any interoffice circuit will be destined to the same outgoing circuit. Therefore all intraoffice transmission is "single shot" or one switchboard operation for each telegram. The intraoffice transmitter, of course, is stopped automatically after each telegram. If a plug is left in a jack after transmission is completed on the telegram for which the connection was established, it will not interfere with subsequent use of the intraoffice circuit by other positions and the circuit allotter will not subsequently re-establish the connection unless the plug is removed from the jack and then reinserted. These operations on the part of the circuit allotter make it practicable for the switching clerk to insert plugs in jacks immediately upon arriving at a switchboard, and then remove that plug from the jack at any convenient time after transmission is completed.

Numbering Messages

Experience has shown that certain safeguards are needed in handling telegrams. One of these safeguards is the use of identifying numbers. These numbers which are in consecutive order starting with number one each day, are affixed and transmitted by transmitting stations and are checked off on number sheets by the receiving stations. Each circuit has its individual series of numbers, therefore a telegram received over circuit *A* under one number, will in all probability be retransmitted over circuit *B* under a different number. This enables the two terminals of each circuit to maintain a constant check on transmission.

In the reperforator switching system it was found to be impracticable to manually insert numbers on telegrams when they were retransmitted. A method was therefore devised to insert these numbers automatically. In order to serve their purpose, numbers must not only be transmitted, but a record must be made at the transmitting office which will indicate which number was assigned to each telegram. This is accomplished by inserting an automatic numbering machine in the intraoffice circuit between the switchboard jack and the automatic perforator on the transmitting circuit. It thus becomes a part of the apparatus associated with the transmitting terminal. When an intraoffice connection is established through the insertion of a plug in a jack and the ensuing operation of the circuit allotter, the automatic numbering machine instantly pre-empts the circuit, transmits its next consecutive number into the automatic perforator and then establishes the connection between the

Figure 3. Switching aisle in receiving section, Richmond, Va.

Figure 4. Supervisory aisle in transmitting section

automatic perforator and the transmitter which selected it. The transmitter then starts automatically and transmits its message. The perforated tape produced by the automatic perforator for transmission on the outgoing circuit will then have the next consecutive number for that circuit immediately preceding the telegram. The tape serves as a record for the switching office to show the relationship of all numbers and their associted telegrams.

Supervisory Measures

In addition to the apparatus employed in the actual handling of telegrams, there are many supervisory devices to facilitate operation and insure safety. In order that switching clerks may know when a telegram has been received on a printer-perforator and is waiting to be transferred through the switchboard to a transmitting circuit, a signal lamp mounted on top of each switchboard lights when a message starts arriving on a printer-perforator served by that switchboard. This indicates to the clerk that a telegram is being received in that group of circuits. Another lamp mounted in a signal indicator panel individual to each printer-perforator also lights to indicate the particular circuit over which the telegram is coming.

In order to provide visual supervision of the functioning of the intraoffice circuits, two small signal lamps are mounted adjacent to the seat of each transmitter plug flush with the switchboard shelf. When a plug is inserted into a jack of the switchboard, one of its lamps will light and remains lighted until the intraoffice connection has been completed and transmission started. When transmission of each telegram is completed, the second lamp will light, indicating that the connection has completed its function and the plug may be removed from the jack.

Since there is a distance of several inches between the punch block of the printer-perforator and the transmitting pins of the transmitter, it is necessary to step out a few inches of blank tape at the end of the last telegram in a group, in order that the last character received may pass through the transmitter. On receiving circuits, push buttons are installed which, when manually depressed, will cause the printer-perforator to step out a predetermined length of blank tape. On transmitting circuits, when the tape between transmitter and automatic perforator becomes taut, the automatic perforator will automatically step out enough tape to allow the last character to pass through the transmitter. When the tape again becomes taut after this operation, no more tape will be stepped out until another telegram has been received.

It may happen that the tape produced by one of the automatic perforators on the transmitting circuits may become broken or jammed in the punch block, or the center holes of the tape stripped so the transmitter will not pull it through. It is very important that such a condition be detected quickly and that the intraoffice connection be maintained until the trouble has been corrected so that a rerun of the tape may be secured. If the connection to the intraoffice transmitter is broken it will be difficult to determine from which transmitter the telegram came. In order to obviate this, alarm circuits are set up to attract attention and to hold the existing intraoffice connection. On the automatic perforator the tape passes between two rollers. The shaft of one roller carries a cam which actuates two sets of contacts in such manner that failure of the tape to move properly while signals are being received by the perforator sets up an alarm signal. When this happens, the action of associated relays will cause the intraoffice transmitter to stop and trouble signals will appear at the automatic perforator position and also at the transmitter position. The circuits are so designed that the trouble at the automatic perforator may be cleared and then by depressing a push button leave the automatic perforator in readiness to function as soon as the tape has been reset in the transmitter. After the tape has been reset at the transmitter, depressing the push button at that position causes the transmitter to start. Transmission cannot be resumed, however, until the push buttons have been operated at both the automatic perforator position and at the transmitting position.

In addition to the problems which concern the actual movement of telegrams, there are problems which relate to good service. Certain classes of telegrams require more expeditious handling than usual. They must be given precedence over other telegrams already in storage or in the process of transmission. In order to accomplish this end, a special position known as the *X* center has been installed. Urgent telegrams are switched direct to this position through special jacks and intraoffice circuits. They are received at the *X* center on printer-perforators in order that their destinations can be quickly read. The transmitters are connected to cords and plugs like the receiving positions of interoffice circuits. A special switchboard serves this center and the jacks are so connected that when a plug is inserted in them, the transmitter at the regular transmitting position is disconnected and stops transmitting, while the transmitter of the *X* center picks up and pre-empts that circuit until transmission of the urgent telegram is completed, at which time the circuit is

restored to its regular transmitter which resumes transmission. Urgent telegrams may be and frequently are transmitted in between the first portion and the last portion of ordinary telegrams just the same as in manual transmission.

Traffic Routing

One of the most important operating features is the routing of telegrams to the circuits which have been designated by the circuit layout and routing engineer as the path over which they shall transit. While Richmond has direct connections with many cities, telegrams are received destined to all parts of the world. Direct connection between all cities and towns is obviously impracticable and it is necessary that telegrams be directed toward various offices having connections with the different cities not reached by Richmond. To systematize the handling and to insure that relay messages receive the minimum number of handlings, routing charts are provided and maintained at each relay office. These charts indicate the proper routing of telegrams for points not worked direct.

Complete route charts, covering outside cities, and the distribution between the various branch offices in Richmond, are located between alternate switchboards. This insures that a clerk will be not over five feet from routing charts at any switchboard.

In case a direct circuit fails, it is necessary to route the traffic over some alternate path and continue this routing until the direct circuit is restored. A small neon lamp associated with each jack indicates the condition of that circuit. When a circuit fails, transmission on it stops, and lights at all switchboards indicate that connections are not to be made to that circuit. It is impossible for a transmitter to start if a connection is made to that circuit and the signal lamp commences flashing and continues to do so as long as the plug remains in the jack. All clerks are notified immediately of irregular routings. This information is placed on a blackboard located so that it is visible from any part of the switching aisle. Information regarding irregular routings is immediately placed on this board, and switching clerks immediately start transmission over the irregular paths.

Spill-Over Positions

Certain practical problems connected with operation make it desirable to provide a means of giving special supervision to some of the telegrams transiting through a relay office. In order to meet this requirement at Richmond, four special positions, termed "spill-over positions," are provided. They are similar to the regular receiving positions, having printer-perforators, intraoffice transmitters, and switchboards. When a telegram is to be handled through one of these spill-over positions, a connection is formed through the switchboard in the receiving section to an automatic perforator in the transmitting section. The tape from this automatic perforator passes through another transmitter which transmits into a printer-perforator at the spill-over position. The reason for passing the telegrams through the automatic perforator rather than directly into the spill-over printer-perforator is due to the fact that the intraoffice transmitters on receiving positions transmit at a speed of 125 words per minute and automatic perforators can accommodate this speed, but printer-perforators are designed to operate at line wire speeds of about 60 to 70 words per minute. Therefore it is necessary to transmit from receiving section to automatic perforator at high speed and then retransmit at lower speed into the printer-perforator of the spill-over position. It is necessary to have these telegrams at the spill-over position in printed and perforated form in order to facilitate supervision and expedite retransmission away from the spill-over position. One of the uses of the spill-over position is in connection with telegrams destined to the smaller communities where the telegraph office is closed at night and for a period of the day on Sundays. During the hours when these small offices are closed other means of getting important telegrams to these points are adopted. Sometimes they are sent to the railroad office in the city of destination, and sometimes they are transmitted to a nearby larger city from which point they are telephoned.

All telegrams destined to closed offices receive close censoring at the last relay office in order to determine whether or not they should be held for the office to open or if other action is necessary. This censoring cannot be delegated to switching clerks, therefore when the signal light on the switchboard indicates that a circuit is closed, the switching clerk switches the telegram to a designated spill-over. Full-rate telegrams and deferred-rate telegrams are transmitted into separate spill-overs. The supervisor censors these telegrams and takes any necessary action. If no action is necessary, full-rate telegrams are immediately switched from the spill-over into the regular storage position and held for the office to open. The deferreds are switched into the regular storage positions some time in the early morning, prior to the opening of the office. As the full rates were switched earlier and are already in the tape at the transmitting position, the outside office first receives these full rates and then the deferreds.

The spill-over positions can be used as sidetracks for telegrams to be held pending restoration of failed circuits in those cases where an alternate routing cannot be obtained.

Double Storage

In the foregoing description of reperforator-switching at Richmond, it has been shown that telegrams are stored twice in the switching office—once at the printer-perforator on the receiving circuits and again at the automatic perforators on the transmitting sides of circuits. It has also been shown that the intraoffice transmission between these two perforators is at a speed of 125 words per minute. The reasons for this "double storage" and "high-speed intraoffice transmission" will now be discussed in more detail.

It would be possible to connect the transmitting terminals directly to jacks in the switchboard and switch the signals received on printer-perforators directly to the outgoing line. That would dispense with the need for intraoffice circuits and secondary storage in automatic perforators on the transmitting terminals. Much less equipment would be required and theoretically the handling would be faster because it would be more direct. Such an arrangement is impracticable. however, where a large number of telegrams are relayed between a multiplicity of circuits. Reception on certain circuits will be continuous for hours. Since the speeds of all circuits are approximately equal, it is apparent that transmission away from the printer-perforators could never be faster than reception. Actually it could never be as fast due to the time required to perform the switching function and due further to the fact that at times the transmitting circuit sought by a printer-perforator would be pre-empted by another printer-perforator. Under such circumstances the number of stored messages would increase steadily and continuously. In order to avoid these difficulties it is necessary to transmit away from the printer-perforators at a rate of speed that is much higher than reception. This intraoffice speed is

125 words per minute, as described later. As the outbound circuits will not accommodate such speed, it is necessary to provide an intermediate handling and step this speed down to approximately 65 words per minute. This is accomplished by using high-speed automatic perforators as individual storage bins, each of which accumulates all of the messages that are to be transmitted over one circuit. This creates a condition where messages are accumulated on transmitting terminals over intraoffice circuits at 125 words per minute and transmission to line is at a speed approximately one-half as fast. This condition is not undesirable, however, for transmission to line is continuous as long as there are telegrams on hand to transmit while reception into the secondary storage over the intraoffice circuit is intermittent. If the total volume of traffic to be transmitted over an interoffice circuit is greater than a speed of 65 words per minute can accommodate satisfactorily, additional facilities must be provided. In this respect the problem is identical with similar conditions under manual operation and is not peculiar to the switching method.

The method used in achieving an intraoffice speed of 125 words per minute has been referred to previously, but it is interesting and will be described in some detail. In printer telegraphy each letter, figure, character, or function is selected by the transmission of five electrical impulses. Individual selection is through the various possible combinations of positive and negative impulses in groups of five impulses per character. The total possible number of selections is approximately doubled by printing one character when the printer is in the lower case or letter shift position and another character when the printer is in the upper case or figure shift position, for each combination of impulses.

On all interoffice telegraph circuits the five impulses of each character are transmitted consecutively, each impulse having the same length or duration of time. By means of synchronous operation of the transmitting and receiving devices, each impulse in a group of five controls an individual selecting magnet, therefore each group of five impulses sets up the selection of a character in the receiving printer.

It is possible greatly to increase the speed of transmission by using five wires between the transmitter and the printer and transmitting all five impulses of a character simultaneously. The cost of providing five wires on interoffice circuits is prohibitive and is not used on such circuits. At Richmond, however, the five-wire system is used in order to provide the intraoffice speed of 125 words per minute. By this means an accumulation of messages at the printer-perforator position can be disposed of at a speed approximately twice as fast as they are being received. This high speed also reduces the time that an intraoffice connection is being used, thus reducing holding time from the various switchboards.

It was necessary, in order to use the five-wire system, to develop special plugs and jacks. These carry nine conductors and the plugs are formed by metallic rings separated by nonconducting rings. The jacks have spring contacts that are so spaced that they fit the metallic rings of the plugs. The four extra connections are used in control and signal circuits (figure 6).

While the plugs are larger than the present standard telegraph and telephone plugs, no difficulty has been experienced by the clerks in manipulating them. The jacks and signal lights occupy about one square inch each on the surface of the switchboard but the switchboard has not proved too large for fast switching. With a much larger installation, it may be necessary to reduce the size of the jacks and plugs, in which case a cam switch or a control plug with relay banks may be substituted.

Conclusions

In concluding this discussion of reperforator switching, it seems in order to summarize briefly a few of the results which have been realized in the Richmond installation since its operation started on October 16, 1937. First, relay business moves through the office in about one-quarter of the time required with manual operation. Second, the capacity of intercity circuits has been increased practically 25 per cent due to the fact that transmitters function continuously as long as there are telegrams to be transmitted. Under manual operation, an operator cannot always keep the transmitter busy, even when there are telegrams awaiting transmission.

Another result is a gain in accuracy, due to the elimination of manual reperforation for the retransmission of each telegram. Finally, operator production, under both average and peak load conditions, has been increased substantially. In spite of this increase, the physical and mental effort required of the operating personnel is much less than in other methods of operation. There are also advantages from the central-office standpoint, since the manual and mechanical distribution of telegrams about an office is done away with and the office equipment occupies considerably less floor space than that used previously.

The Richmond installation has successfully withstood every test of practical operation, and has demonstrated its superiority under all conditions. In

Figure 5. Operating positions in manual section

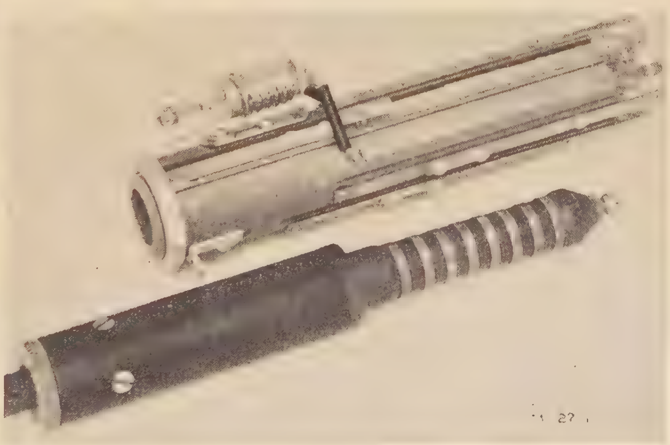

Figure 6. Jack and plug used in nine-wire transmission

Surge-Voltage Breakdown Characteristics for Electrical Gaps in Oil

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FELLOW AIEE

Synopsis: This paper, emanating from a request for information regarding surge voltages required to break down gaps in oil, gives surge breakdown voltage values with different gap spacings for $^1/_4$-inch, $^1/_2$-inch, and 1-inch round rod electrodes with hemispherical ends immersed in transformer oil. As expected, these values are a function of "time to breakdown" but for each condition curves show constant breakdown values for breakdown times of the order of about 16 microseconds and longer with the $1^1/_2 \times 40$ negative wave, used on all the tests reported. Particular attention is called to the relatively small amount of oil required for tests of this type, made possible by the special type of test barrel used.

INSULATION co-ordination and oil-circuit-breaker designs make desirable a knowledge of surge voltages required to break down insulating oil. The lack of data pertaining to this subject was called to our attention by E. K. Sadler and J. L. Thompson, engineers with the Kelman Electric and Manufacturing Company. The test results published in this paper were made possible by the co-operation of J. N. Kelman, who provided some of the equipment required for making the tests, and by a great deal of arduous and careful work done by graduate students, particularly G. D. McCann and A. E. Harrison, in the high-voltage laboratory at the California Institute of Technology.

Voltage for making the tests was obtained by means of a 1,500,000-volt Marx circuit surge generator comprising 30 50-kv 0.5-microfarad General Electric capacitors and a suitable d-c charging circuit. The test gaps in oil were formed by using specially constructed electrodes assembled in a test barrel devised by the author and shown in figures 1 and 2. All tests were made with a standard $1^1/_2 \times 40$ negative wave. The voltage for each discharge was measured by means of a cathode-ray oscillograph of the cold-cathode continuous-beam type designed and built by Doctor Howard Griest,[1] and a resistance potentiometer constructed according to the required standards for such work. Figure 3 shows a typical oscillogram. The voltages thus measured were at intervals checked as to peak values by comparison with standard sphere gaps.

All gap test electrodes used were round rods terminating as hemispheres having the same diameter as the rods. This type electrode was chosen in preference to spheres mounted on rods or shanks in order to avoid under surge conditions, uncertainties regarding the influence of shank diameter upon the field uniformity around the gap, and, hence, upon the results obtained by our tests.

Electrodes ranging from one-fourth inch to six inches in diameter were prepared. This report contains data for electrodes having diameters of one-fourth, one-half, one inch, and two inches, respectively. The data for the two-inch electrodes are less complete than for the other rods, because the voltage available, 1,500 kv, would not permit tests with the two-inch electrodes at the larger spacings. An increase in surge-generator voltage is being made and further tests will be reported in a later paper.

One reason for the absence of data of the type presented in this paper has been the difficulty encountered in providing a convenient lead-in bushing for making tests of this type. This difficulty we overcame by making a test barrel in which the electrodes were mounted, and its lead-in bushing of insulating material having about the same dielectric constant as insulating oil. Fortunately, we had available for making this device two cylinders made of paper and varnish, known by the trade names Micarta and Herkolite, respectively. The larger cylinder, 40 inches in diameter and 72 inches long, forms the test chamber, and the smaller one, $23^3/_4$ inches in diameter and 48 inches long, serves as a lead-in bushing. These cylinders were open at both ends when obtained. An oil-tight bottom for the test barrel was obtained by placing the insulating cylinder upon a steel plate on the surface of which a circular gasket seat had been machined. A cork gasket which could be clamped tightly between the end of the cylinder and the gasket seat was used. A steel clamping band, as shown in figure 2, drawn tightly around the Micarta cylinder by a bolt and drawn down hard upon the cork gasket by bolts through studs welded to the band and engaging threaded holes in the steel bottom, provided means for keeping this cork-gasket joint tight. Any oil leakage which might occur, due to accident or other cause, was amply provided for by placing the test barrel in a shallow oil-tight steel receptacle, large enough to hold all the oil used. With this arrangement, requiring only eight barrels of oil, the test electrodes are freer from field distortion due to adjacent materials than would be possible with the use of containers of metal or other conducting or even semiconducting material, unless such containers were made very large. That is, the use of oil in a barrel of insulating material having about the same dielectric constant as oil, makes possible with a small amount of oil, electric gaps immersed in what, in effect, is a column of oil insulation surrounded by the atmosphere of the test room.

Calculations before construction, and tests after construction, show, for all practical purposes, that this device provides a means of having test gaps in oil completely free from field distortion due to surrounding objects.

The Herkolite cylinder serving as the lead-in bushing is closed at the lower end with a fiber and metal bottom designed to hold oil between it and a steel tubing concentric with the insulating cylinder and through which the upper and adjustable electrode extends into the test barrel. This metal part of the bottom is constructed in such a way as to provide for a well-distributed electric field around the

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1. For all numbered references, see list at end of paper.

periods of subnormal loads, such as Sundays and late night hours, it permits the highest degree of concentration of work. In times of abnormal loads, such as Christmas, New Year's, Easter, or special events of national interest, it expands naturally to accommodate itself to the increased burden. Under all conditions, it handles the telegrams with greater speed and accuracy than ever before, and thus has brought about significant progress in the telegraphic art.

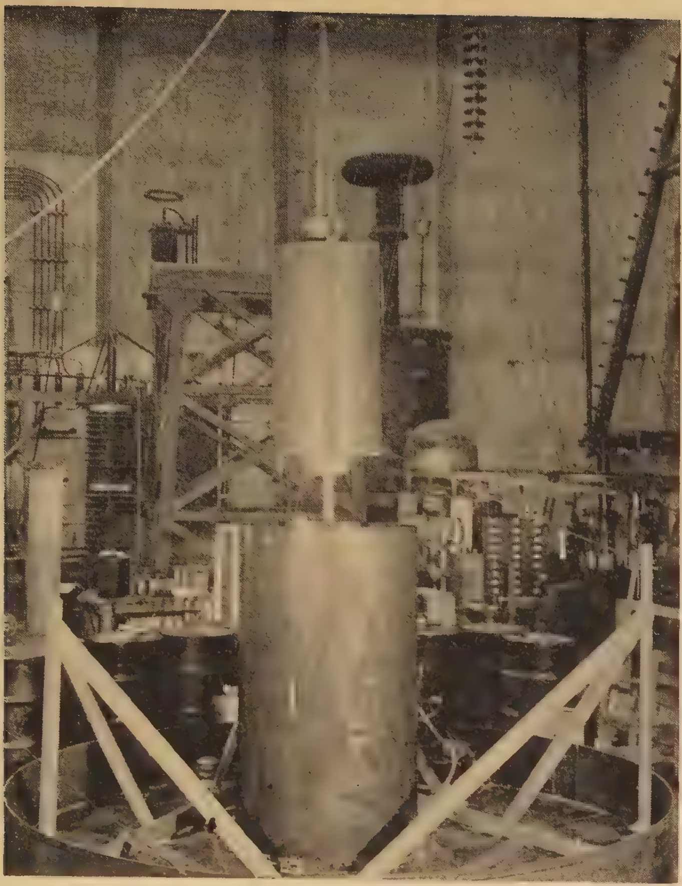
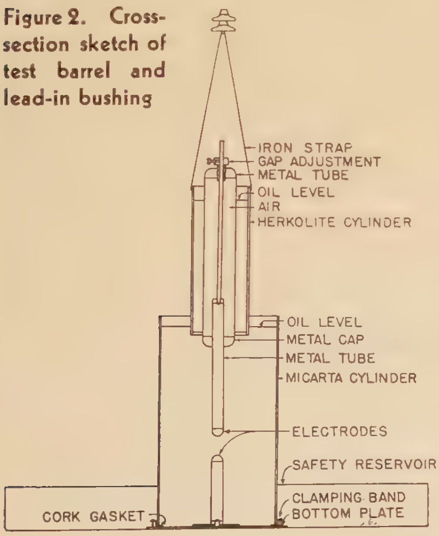


Figure 1. Test barrel and lead-in bushing showing bushing raised for examination and polishing electrodes

lower end of the bushing. The lower electrode, supported by and attached to the bottom of the barrel, was not made adjustable, but constructed so as easily to be changed or removed for cleaning and polishing. During tests the part of the lead-in bushing between outer and inner cylinders is kept filled with oil and flashover from lead-in conductor to the barrel is avoided by having its lower end project into the test barrel a few inches below the surface of the oil in the barrel. This arrangement was proved entirely satisfactory as a means of limiting all arc-overs to the test gap.

Figure 2. Cross-section sketch of test barrel and lead-in bushing



The tests reported in this paper show only the surge voltages required to break down gaps in oil formed between spherically ended cylindrical electrodes of different diameter. All oil used was carefully selected, filtered, and tested according to standard oil testing practice before starting the tests and as often during any test as was necessary to keep the dielectric strength at top value, this top value being determined by a standard oil gap test set capable of applying 30 kv to the one-tenth inch test gap formed between one-inch-diameter flat electrodes. The oil was considered in proper condition when it would not break down for a two-minute application of this voltage. To keep the oil up to this standard during a test program was not easy, filtering often being found necessary after only a few oil punctures had been made; and frequently after the puncture value of the oil had been decreased, it was necessary to put the oil through the filter several times to restore its dielectric strength to 30 kv. Whenever the dielectric strength of the oil dropped to a value of 22 kv or less, the surge voltage required to break down any given gap was reduced an amount which indicates that perhaps as further tests of this type are made, the dielectric strength of the oil during a test run should be determined after practically every oil breakdown. Also, if we wish to know the reason for some of the variable results obtained, it may be necessary to determine oil puncture strength with a precision which will show small variations in dielectric strength in the range above 30 kv, as determined with the standard test cup.

Early in our test program we found that, for consistent breakdown values, only a few discharges could be made between electrode polishings. This was more noticeable for the smaller electrodes than for the larger ones. On rare occasions only one or two discharges which, perchance, occurred from the same spot on one of the electrodes, would make necessary a repolishing of electrodes before consistent breakdown values could be obtained. In all tests it was necessary to observe a time interval of not less than 5 minutes between successive discharges, and for the longer gaps time intervals of 15 to 20 minutes were required for the oil to return to what might be called a normal state.

These influence factors, plus the all-prevailing time-lag influence upon surge-breakdown values of voltage for gaps in oil, added to those well-known difficulties encountered in obtaining similar data at power frequencies, soon made evident the fact that breakdown values for gaps in oil would have to be considered as statistical values obtained from a large number of tests, some of which would show values of breakdown voltage varying a considerable amount from any curve drawn to show the probable reasonable breakdown values. In fact, surge-voltage-breakdown values in oil seem to be even

Figure 3. Typical oscillogram, showing oil puncture occurring at 860 kv crest and 9½ microseconds time lag for eight-inch gap, one-half-inch-diameter electrodes

more sensitive to the influences which make testing such gaps at power frequency a major operation, than is the case for the power-frequency tests; and it may almost be said that on some days sport breakdown values occurred, for which there just seems to be no way of accounting.

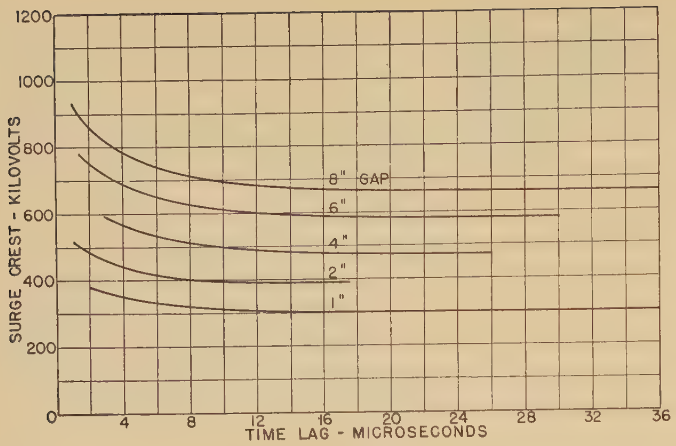


Figure 4. Time-lag curves for one-fourth-inch electrodes with hemispherical ends, $1\frac{1}{2}$x40-microsecond wave

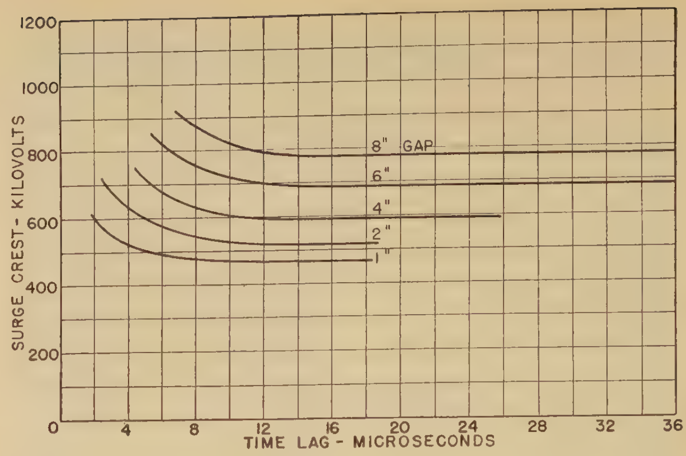


Figure 5. Time-lag curves for one-half-inch electrodes with hemispherical ends, $1\frac{1}{2}$x40-microsecond wave

In making the volt-time tests, the operating procedure was as follows: The surge generator was adjusted to give a $1^1/_2$x40-microsecond negative wave having a crest value well below the minimum flashover voltage required to strike across the gap under test, and for this setting a surge was applied to the gap. The voltage was then increased by small steps until a voltage was reached which would puncture the oil in the gap. When breakdown occurred, the surge voltage which first caused breakdown was applied a number of times. If breakdown occurred for every surge application, the voltage setting on the generator was reduced until breakdown stopped, after which the voltage was again raised until it reached the minimum value which would give breakdown for a majority of the applications.

As a check on this breakdown value, the surge-generator voltage would be alternately raised and lowered above and below the probable breakdown values. Often a one-step change on the surge generator (about three per cent) in the crest voltage value either way would change breakdown performance so that with a three per cent lowering of the crest voltage there would be no breakdowns at all; whereas with a three per cent increase in crest voltage practically every surge application would cause a breakdown.

Having in this way established the probable minimum breakdown voltage for a given gap setting and electrode size, the balance of the volt-time curve was obtained by applying the $1^1/_2$x40-microsecond wave at increasing voltages and taking cathode-ray oscillograms of the voltage across the oil gap under test. For each surge-voltage application an oscillogram was made to show the value of the wave from the time of tripping the circuit to breakdown. Figure 3 is a typical oscillogram. In most cases breakdown occurred on the tail of the wave. The crest values of the waves thus recorded were plotted as ordinates on the curve sheets shown in figures 4, 5, 6, and 7, with the time to breakdown shown as corresponding abscissas. The curves thus obtained show minimum breakdown voltages and breakdown voltage versus time to breakdown for higher voltage values. Figure 7 shows the same curve for two-inch spacing, as shown on figure 6, but shows also the exact location of the points used in plotting the curve.

The probable breakdown curves shown in the paper are considered correct as to values given for prevailing conditions within a value of plus or minus three per cent. Occasionally, however, voltages more than ten per cent above the probable breakdown values shown in the curves would be required to cause breakdown. We think such discrepancies were due to undetermined variable conditions of oil and electrode surfaces, but up to the present time our analysis does not permit a statement as to what these conditions were.

When one of these extremely high first-breakdown voltage conditions was encountered, the test procedure outlined

Figure 6. Time-lag curves for one-inch electrodes with hemispherical ends, $1\frac{1}{2}$x40-microsecond wave

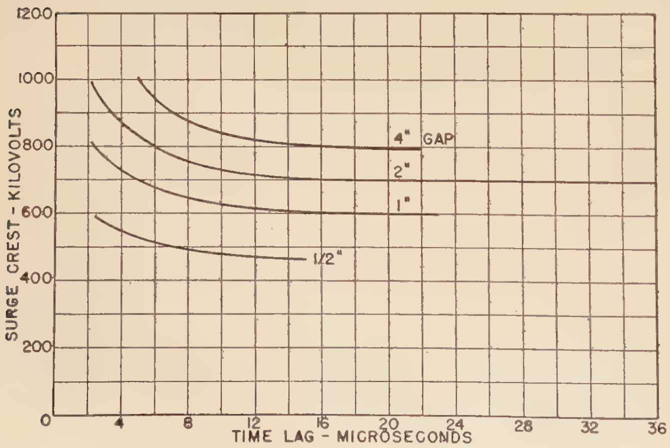
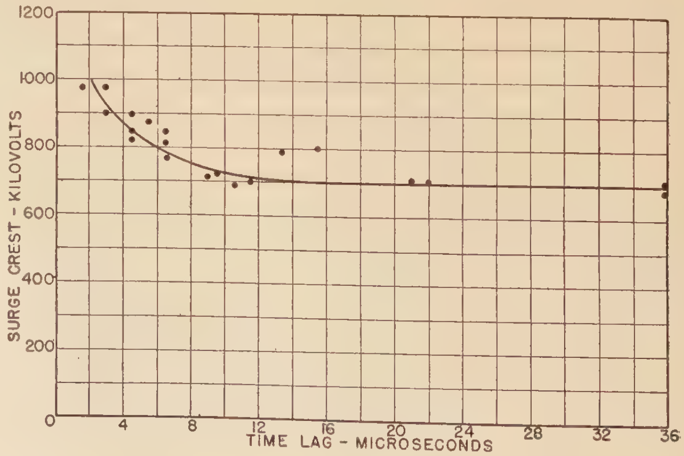


Figure 7. Time-lag curves for one-inch electrodes with hemispherical ends, showing spread of actual plotted values from which curve was obtained; $1\frac{1}{2}$x40-microsecond wave



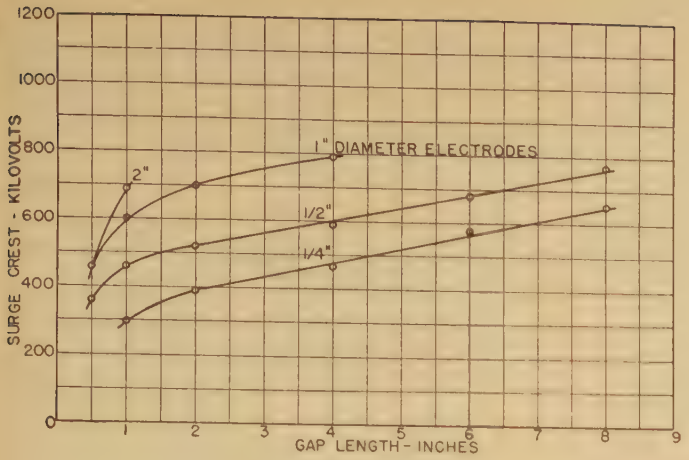


Figure 8. Curve showing relation of gap length to minimum surge crest voltage required for breakdown between cylindrical electrodes with hemispherical ends immersed in oil, $1\frac{1}{2} \times 40$-microsecond wave

was reversed and, subsequent to the first breakdown, surges of lower crest voltage than the one causing this first breakdown, but higher than the recognized minimum breakdown, were applied. The voltages for the successive tests were gradually reduced until the probable minimum breakdown voltage for any given gap was reached. The minimum values of voltages found in this manner were in agreement with those found for the same gaps by the more commonly used increasing-voltage procedure. For the one-fourth-inch rods no excess-voltage first breakdowns were in evidence. For the one-half-inch rods this effect was indicated only, and then was limited to the longer gaps. The one-inch rods showed a very pronounced tendency to be subject to this phenomena at small spacings and for the longer gaps high breakdown points definitely occurred. The two-inch rods showed occasional high breakdown voltages for short gaps. If continued tests show any appreciable increase in the percentage of high-breakdown-voltage values, it may be necessary for the larger electrodes to indicate arc-over voltage by a broad curve showing the spread, rather than by a single-line probable-breakdown curve.

To show more explicitly what this phenomenon of high breakdown signifies, the following specific instances of such occurrence are noted.

July 11, 1938, five successive surges, all with crest voltage values more than 10 per cent above the probable minimum breakdown value applied to the one-inch gap between one-inch electrodes, failed to puncture the oil. The sixth, or puncturing surge, had a crest value 24 per cent above what appears to be the probable minimum puncture value for the gap.

July 13, 1938, with the same electrodes and same setting, five surges with crest voltages more than 10 per cent above the probable minimum breakdown voltage failed to puncture the oil. Puncture finally occurred at a crest voltage 17 per cent higher than the probable minimum.

July 14, 1938, seven surges which failed to puncture the oil had crest values more than 10 per cent above the probable minimum value applied to one-inch electrodes spaced for a two-inch gap. The breakdown finally occurred at a crest voltage 21 per cent higher than the probable minimum value for this arrangement.

Figure 8 shows data rearranged to enable one to obtain readily the relation between gap lengths and minimum puncture voltages for the gaps included in this report.

It is well to note that the limited amount of data available for design calculations as gleaned from the 1,500 surge tests made to obtain the data presented in this report point strongly to the need of continuing this work in a broader test program extended to a number of our high-voltage laboratories. A search for data pertaining to similar tests for a-c 60-cycle voltage which might be used in making comparison between 60-cycle and surge dielectric strengths of oil gaps[2] disclosed the fact that published 60-cycle data in agreement as to values for gaps formed between different types of electrodes in oil are by no means adequate for our present requirements. Although the ratio of surge crest $1^1/_2$x40-microsecond wave voltages to 60-cycle crest voltages required to puncture oil when such voltages are applied to immersed sphere gaps varies with the size of spheres and gap spacing, the present available data indicate that no great trouble will be encountered in designing apparatus if this ratio of crest surge voltage to power-frequency root-mean-square voltage is taken as three to one until sufficient data for better conclusions are available. Tests made by F. W. Peek[3] when he introduced the idea of time lag show this ratio of three to one for surges of unknown wave form as compared to 60-cycle breakdown voltages in oil.

To obtain these further data, we invite co-operation from others interested in high-voltage phenomena and recommend the use of test barrels and lead-in bushings made of insulation material having about the same dielectric constant as the insulating liquids to be tested and built according to the general plan of the apparatus described in this paper.

References

1. A Low-Voltage High-Speed Cathode-Ray Oscillograph, R. Howard Griest. Thesis for doctor of philosophy degree, California Institute of Technology, 1937.

2. Oil Breakdown at Large Spacings, Douglas F. Miner. AIEE Transactions, 1927, page 248.

3. Dielectric Phenomena in High-Voltage Engineering (a book), Peek. McGraw-Hill Book Company, 1929, page 227.

Discussion

D. C. Prince (General Electric Company, Philadelphia, Pa.): This paper adds valuable information to our store of knowledge on the behavior of insulating oils. One point of particular value to circuit-breaker designers is brought out very clearly. Under all the conditions investigated the oil presents an impulse ratio of from 2 to 3. Ordinary air clearances, rod gaps, bushings, and the like, associated with circuit breakers, have impulse ratios of the order of 1.2. It follows that failure of the oil under impulse is not limiting, a fact of obvious value to designers.

V. M. Montsinger (General Electric Company, Pittsfield, Mass.): Professor Sorensen has given us some very interesting impulse data on the breakdown of oil. Apparently, by exercising great care, he has been able to eliminate the wide variations in oil-breakdown values that usually occur in ordinary methods of testing.

There are, however, two or three points I wish to comment on.

The author apparently used hemispherical-shaped electrodes to simulate conditions in circuit breakers. The variation of the breakdown voltage with spacing does not seem to follow any law that I have ever observed. For example, his figure 8 shows that for the one-fourth-inch and one-half-inch-diameter electrodes the breakdown voltage varies roughly as the spacing raised to the 0.37 power. For one-inch-diameter electrodes the exponential value of the spacing is even less than 0.37 and bends over, indicating that considerably greater spacings than four inches would give very little increase in breakdown values.

Generally when spheres are used with spacings several times their diameter they act like sharp-cornered electrodes, so far as breakdown versus spacing is concerned. This is especially true when air is the insulating medium.

We have a large amount of data on breakdown of oil for square-edged and round

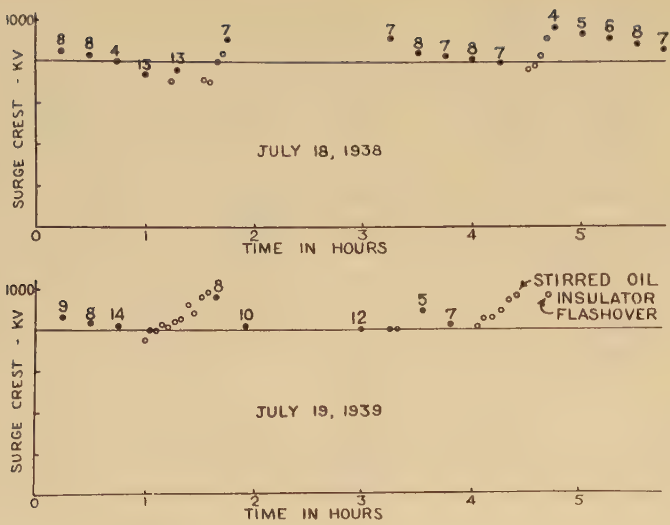


Figure 1

rods (both parallel and at right angles) and in all cases the breakdown is roughly proportional to the spacing raised to the two-third power. It appears from Professor Sorensen's data that for limited spacings—up to six or eight inches—and with small diameter electrodes, the breakdown voltage increases quite slowly with spacing. It would be interesting to know if circuit-breaker engineers find that this is true for the kind of electrodes used in circuit breakers, or do they find that the breakdown strength varies roughly as the spacing raised to the two-third power.

Eric A. Walker (Tufts College, Medford, Mass.): The paper by Professor Sorensen on the "Surge-Voltage Breakdown Characteristics for Electrical Gaps in Oil" is of considerable interest to me because it is very similar in nature to a study which has been started at Tufts College.

In making surge breakdown tests I have felt that one of the most important factors in determining the breakdown strength of the oil is the amount of moisture the oil contains; a factor which is not mentioned by Professor Sorensen, except to say that the oil was periodically filtered.

Oil in contact with air undoubtedly contains water in two forms: water in solution and water suspended as small droplets which gradually settle out and collect as free moisture at the bottom of the tank. The balance between the two types is controlled by the temperature. As the oil cools less water is held in solution, and more in suspension. I do not believe that moisture in one form will have the same effect as moisture in the other, so I feel that before consistent results can be obtained the total amount of moisture the oil contains and the temperature must be controlled and recorded.

If oil contains moisture in suspension it appears difficult to reproduce results because each successive shot draws more moisture into the gap. The reason is self-evident. Water has a higher dielectric constant than oil and so is impelled into the region where the electrical stress is greatest.

In our tests a number of sludged samples of oil were found, which had relatively high breakdown strengths when tested on a short chopped wave; and relatively low strengths when tested at 60 cycles in the standard gap. The power factor of these sludged samples was high.

I wonder if Professor Sorensen does not emphasize too much the advantages of constructing a tank of Herkolite or some other material which has a dielectric constant about the same as oil. It is true there will be little field distortion at the oil-Herkolite boundary, but very close to it is the Herkolite-air boundary, where there is a change of dielectric constant and a distortion of field.

A. E. Harrison (California Institute of Technology, Pasadena): A diagram showing the time of application of surges to the one-inch electrodes at four-inch spacing has been prepared to illustrate the phenomenon of application of crest voltages above the probable minimum value without breakdown. Figure 1 of this discussion shows two runs made July 18 and July 19, 1938. The ordinates of the points represent crest voltages, while the time in hours gives the intervals of time between application of surges. The figures above certain points give the breakdown time in microseconds. No breakdown occurred for surges indicated by open circles.

I interpret these data as follows: Application of surge voltage less than that required for breakdown changes the condition of the electrode surface, and/or the condition of the oil so that the gap will not break down when the probable minimum value of crest voltage is exceeded. The influence of operating procedure has not been established, although recent evidence points to the conclusion that the stirring of the oil after breakdown has occurred may account for this behavior. Stirring the oil when breakdown had not occurred, and waiting 15 minutes (the next to last point on July 19 and other similar tests not illustrated) would not cause breakdown to occur, however. Once breakdown has occurred at a high voltage, breakdown will then occur at the probable minimum voltage. (Note point at time two hours on July 19.)

This unusual behavior was quite consistent on days when it occurred, but there were times when the phenomenon failed to occur for no apparent reason. Also, this phenomenon did not seem to occur when the oil around the gap was not stirred after a breakdown, although failure to stir the oil seemed to reduce the strength of the oil in

Figure 2. Time-lag curves for one-inch electrodes with hemispherical ends, 1½ x 40-microsecond negative impulse wave

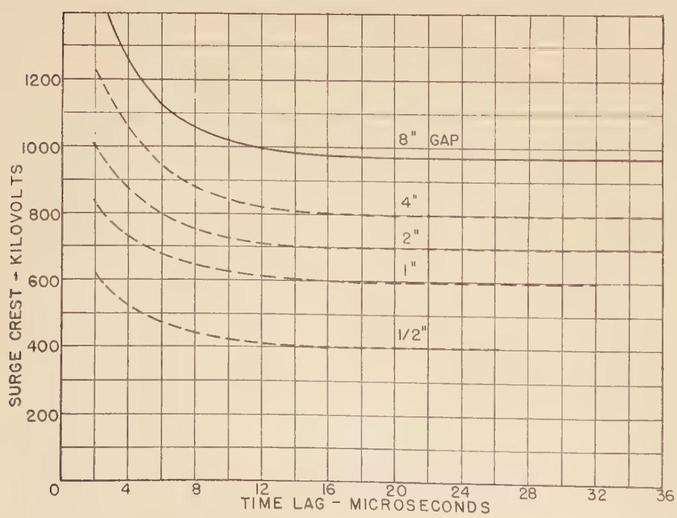
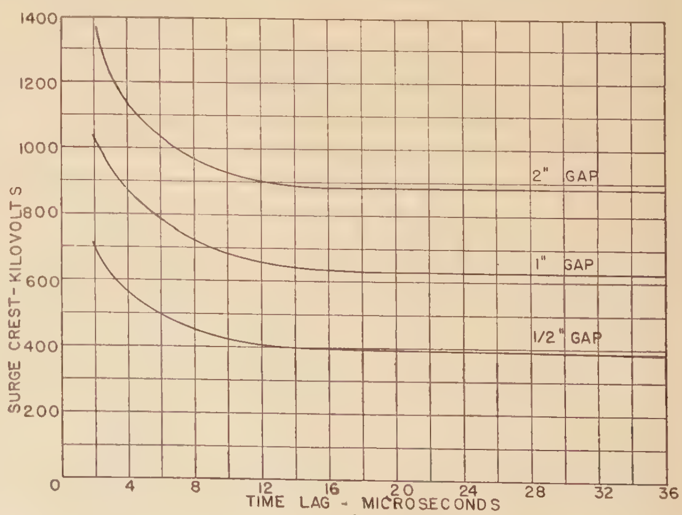


Figure 3. Time-lag curves for two-inch electrodes with hemispherical ends, 1½ x 40-microsecond negative impulse wave



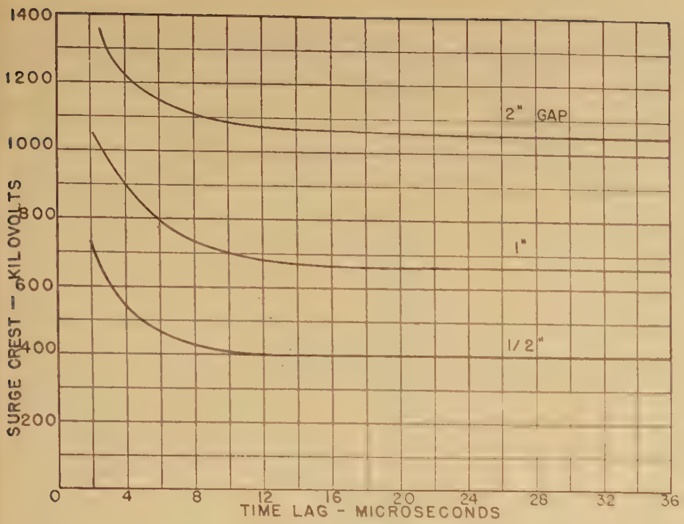


Figure 4. Time-lag curves for four-inch electrodes with hemispherical ends, $1\frac{1}{2} \times 40$-microsecond negative impulse wave

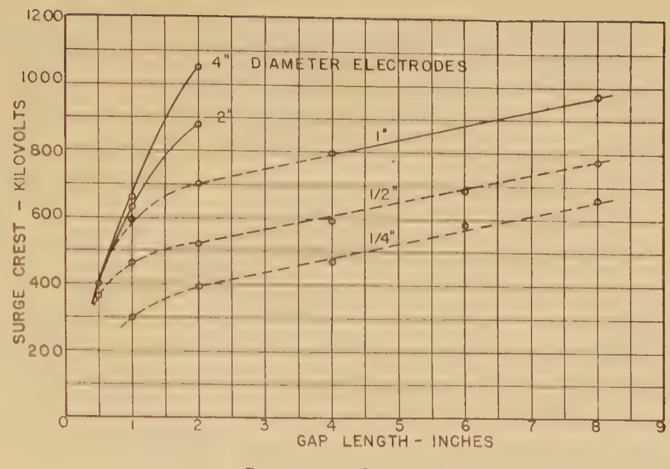


Figure 5. Curves showing relation of gap length to minimum surge crest voltage required for breakdown between cylindrical electrodes one-fourth-inch, one-half-inch, one-inch, two-inch, and four-inch diameter, with hemispherical ends, the gaps being immersed in transformer oil and subjected to $1\frac{1}{2} \times 40$-microsecond negative impulse waves

some cases. We would be interested in hearing possible explanations of this unusual behavior.

A. Lovoff (California Institute of Technology, Pasadena): I would like to present additional data on the breakdown characteristics of oil, obtained in the high-voltage laboratory of the California Institute of Technology subsequent to the writing of Doctor Sorensen's paper.

Figures 2, 3, and 5 of this discussion show an extension of the data for the one- and two-inch electrodes and figures 4 and 5 show data for the four-inch electrode not included in the paper. The dotted curves are the same as those presented by Doctor Sorensen in his paper and are reproduced in this discussion for the sake of completeness. The curves of figure 5 and a curve for point electrodes if all plotted on one log-log plot will show for the larger gap spacings the manner in which the curves for the various-diameter electrodes approach the needle-gap curve. Such a log-log plot will be included in a paper now in preparation, hence will not be given in this discussion.

Recent preliminary power-frequency-voltage breakdown tests on these electrodes to determine the one-minute hold voltage disclose that the ratio of minimum surge breakdown voltage to the one-minute-hold power-frequency voltage (crest) is approximately 2.2. This impulse ratio of 2.2 checks with the figure given by Doctor Sorensen.

The anomaly of the application of greater than the established minimum breakdown surge voltages without oil breakdown occurring, as discussed by A. E. Harrison, may possibly be explained as follows. After the oil has been broken down in the gap and the oil stirred, a high enough concentration of carbon particles might remain in the vicinity of the gap to distort the field in such a way as to increase the breakdown voltage. I have noticed this failure-to-breakdown phenomena at higher than the established minimum surge voltage when testing the one-inch electrodes at the four- and eight-inch spacings. In that case the oil after being subject to several successive shots at higher than the probable minimum breakdown surge voltage without a resulting oil breakdown was restored to a normal breakdown status by proceeding as follows: the oil was very thoroughly stirred and after a ten-minute wait subjected to a surge voltage just above the probable minimum, when it was found to resume a normal performance. Three such instances noted in my records tend to substantiate the contention that foreign matter introduced during breakdown is the cause of this no-breakdown phenomena at voltage values higher than the probable minimum surge breakdown voltage.

Royal W. Sorensen: Mr. Montsinger's comments are valuable additions to the bit of information regarding surge-voltage performance for electrical conductors in oil included in this paper, which we hope has initiated a program of testing that will give us a more extensive knowledge of surge voltage performance.

All of the statements in our papers do not seem to convey to Mr. Montsinger the same meaning as that which we intended. Our reason for using rods with hemispherical ends as electrodes was not to simulate the conductors in circuit breakers, because circuit breakers do not use electrodes of that shape. The electrode shape we used was chosen because the sphere gap is a standard method of making voltage measurements. Spheres in oil with supporting shanks of small diameter, however, are more susceptible to shank influences than are similar spheres in air. Hence to avoid possible variations in arc-over voltage due to differences in shank sizes which might be used, rod electrodes with the ends rounded off as hemispheres were used.

Subsequent to the writing of the paper under discussion, we have made tests which have given us much data not available for the paper. Some of these additional data are recorded in the curves of figure 5 of Mr. Lovoff's discussion. It is interesting to note that the extended curves including these additional data are satisfactorily in accord with the curves of the paper's figure 8, to which Mr. Montsinger has referred. It is true that for the larger spacings, as Mr. Montsinger has pointed out, not only the one-inch-diameter electrode, but also the other electrodes show smaller increases in voltage breakdown values as the spacings are increased. When, however, we can obtain a high enough voltage to get out on the straight-line parts of the curves, as has been done for the one-fourth-, one-half-, and one-inch electrodes, it is interesting to note that the curves are approximately parallel when plotted on rectangular co-ordinate paper, as is the case for figure 8 of the paper under discussion, and figure 4 of Mr. Lovoff's discussion.

Mr. Montsinger states that "generally when spheres are used with spacings several times their diameter, they act like sharp-cornered electrodes so far as breakdown versus spacing is concerned." Some of our data, not yet published, bear this out, because for all electrodes when the spacing is sufficiently increased, we find that the curves of breakdown voltage versus gap length for the electrodes approach the point-gap curve.

Mr. Montsinger calls attention to the fact that he has available "a large amount of data on breakdown of oil for square-edged and round rods (both parallel and at right angles) and (that) in all cases the breakdown is roughly proportional to the spacing raised to the two-third power." I presume he refers specifically to surge-voltage breakdown. I would be interested in seeing these data, not only to note what the surge breakdown values are, but also to note whether parallel and crossed rods for surge voltages have (as is the case with power-frequency voltages) the same breakdown values for parallel and crossed rods, a fact long ago noted in Schwaiger's "Theory of Dielectrics."

Mr. Montsinger also states that for limited spacings up to six or eight inches the voltage increases slowly with spacing. Also an inspection of the curves shows that with such spacings tests on electrodes having diameters of one inch or less give for these spacings curves that are approximately straight lines. I cannot, however, give any information as to what circuit-breaker engineers find for the kind of electrodes used in circuit breakers because I have not seen any published data for such tests. The reason for the small amount of such data available

is perhaps found in D. C. Prince's discussion of our paper, wherein he says "under all the conditions investigated (and reported in the paper) the oil presents an impulse ratio of from 2 to 3, whereas the parts of the breaker which are in air have impulse ratios of the order of 1.2." In other words, what we have done is verify the fact that oil under impulse is not a limiting factor in design because oil strength under normal and recovery voltage has taken care of the impulse factor.

E. A. Walker's discussion calls attention to the importance of giving careful attention in making these studies to the amount of moisture in the oil under test and the form in which the moisture is present. Very early in our experiments, as was stated in the paper, we found that breakdown values were very sensitive to the oil moisture content. So far we have simply avoided most of the difficulties of variability due to this moisture content by using only oil of high dielectric test; for example, oil which would stand 30,000 to 40,000 volts when tested with a standard 0.1-inch oil testing gap. In fact, as Mr. Walker suggests, there is no doubt a fertile field for investigation to determine the exact quantitative influence of water content and also of temperature on surge-voltage-breakdown values for oil.

I do not think, as Mr. Walker has stated, that we have at all overemphasized the advantages of using a test tank of material which has a dielectric constant approximately the same as that of oil, because after all the prime reason for the use of a tank made of insulation material rather than metal is the avoidance of the difficult lead-in bushing problem and the use of the large amount of oil required when steel tanks are used. The fact that the dielectric constant of the insulation material used is so nearly the same value as the constant for transformer oil and that the dielectric constants for both the oil and the insulation material is only two to three times the constant for air, is a happy coincidence which makes our plan practical; whereas it would not be so good if we had to use a barrel made of some material such as porcelain, which has a much higher dielectric constant than the material of which our test barrel is made.

At present I have no explanation for the phenomena described in Mr. Harrison's discussion and can only confine my remarks to expressing appreciation of the large amount of careful, conscientious work which he has done in obtaining for me much of the data used in this paper.

Mr. Lovoff also has added to the paper data which he has obtained and which extend the curves used in the paper to values beyond those available at the time the paper was written. To him and to other students who have helped in this work, I am deeply indebted, for without their help the large amount of testing necessary to produce this report could not have been obtained. In fact, like most research work of today, the results presented in this paper are available only because of much co-operation by many persons and it would certainly be unfair to close our discussion without expressing appreciation to the Kelman Electric and Manufacturing Company, which provided much of the equipment used in making the tests, and to Messrs. Kelman, Sadler, and Thompson, who contributed valuable suggestions.

Sensitive Ground Protection for Radial Distribution Feeders

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THERE are three reasons for isolating or de-energizing grounded feeders: first, danger to life; second, danger to property; and third, to permit joint use of pole lines with the telephone companies. The first two are very difficult to evaluate, but in certain territories a means of isolation is very important. The third reason can be given a definite value, and the economies resulting from joint use of pole lines can more than justify this proposed scheme of sensitive ground protection for radial feeders.

This paper will not discuss the merits of leaving a ground-faulted feeder in service for the continuity of service, as may be the practice by some utilities, but discusses the methods of clearing ground faults that may normally occur on radial feeders.

Ground Faults

The magnitude of ground currents on lower-voltage feeders with solidly grounded neutral transformers varies more according to the contact resistance of the fault than it does for the location of the fault. This effect is greater, the lower the voltage of the circuit.[1] The usual voltages used for radial feeders range from 2.3 kv to 22 kv.

Many ground tests have been made on 2.3-, 4-, 7-, 11-, and 16.5-kv systems of the Southern California Edison Company, Ltd. These tests all have shown conclusively that the contact resistance has a controlling influence on the magnitude of ground current.

Tests on a 4-kv solidly grounded neutral circuit show very small amounts of current when bare wire is ground-faulted as follows: In dust 0.3 to 0.6 amperes, in grass 1 to 3 amperes, in muddy water 25 to 30 amperes. Other tests on 4 kv on dry pavement and dry sand soil, where there had been no rain for several months, show that practically no current flows. A series of tests were made on a 7-kv impedance-grounded neutral system by dropping a 2/0 bare conductor on a green lawn. In this case, with about 20 feet in contact, the current was in the order of 2 to 3 amperes during the few minutes of each test. In another test, with a ground connected to a five-gallon can in mud, 35 amperes flowed in an 11-kv solidly grounded neutral circuit. Tests were made on 16.5-kv solidly grounded neutral circuit by dropping a partial span in a dry stubble field. It was necessary for the conductor to touch a green weed or come in contact with a conducting portion of earth before current would flow. Some of the times the conductor would lie in this stubble field as if dead; then all of a sudden a breakdown to earth would occur which was sufficient to cause current to flow. From this particular group of tests it seemed as though at certain times, when the conductor was dropped, it would break down,

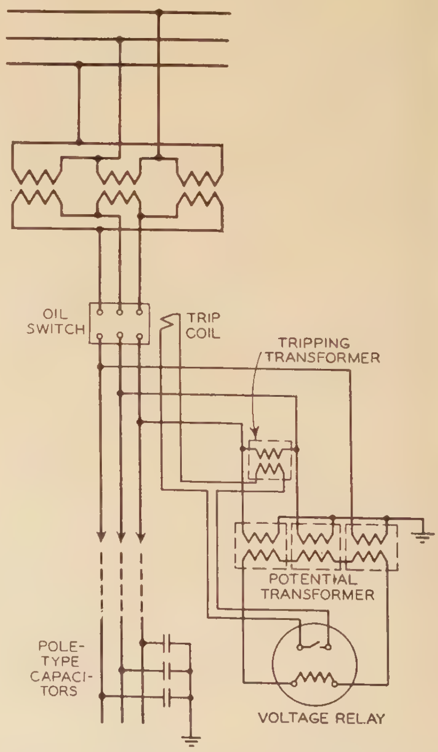

Figure 1. Sensitive ground protection for single-circuit delta system

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LLOYD F. HUNT is protection engineer and J. H. VIVIAN is technical assistant and superintendent of relays, Southern California Edison Company, Ltd., Los Angeles.

1. For numbered reference, see end of paper.

and at other times it would not. It seemed to be a critical voltage where, when in contact with earth, a breakdown would occur. It can be conceived that there is a breakdown phenomenon that is governed by voltage, current, and size of conductor, or area of actual contact surface with earth. That is, there is, under a given condition, with a conductor on dry earth, a value where practically no current flows, but by raising the voltage to a critical value, a breakdown occurs, causing current to flow. There may be a variation of this point, but it will be safe to say that the lower the voltage, the more often the breakdown will fail to occur, and the higher the voltage, the more often the breakdown will occur.

From past experience, this critical voltage under normal operating conditions seems to be between 11 kv and 22 kv. Of course, there are exceptions both ways. In other words, there are times when an 11-kv circuit breaks down, and there have been times when a 33-kv line has apparently failed to break down.

This subject of breakdown is of sufficient importance to warrant some research so that engineers, as a whole, would have a common understanding of earth faults.

With this study in mind, showing that it is possible to have earth faults that have practically no current and solid ground short circuits that have many thousand amperes, a method was sought

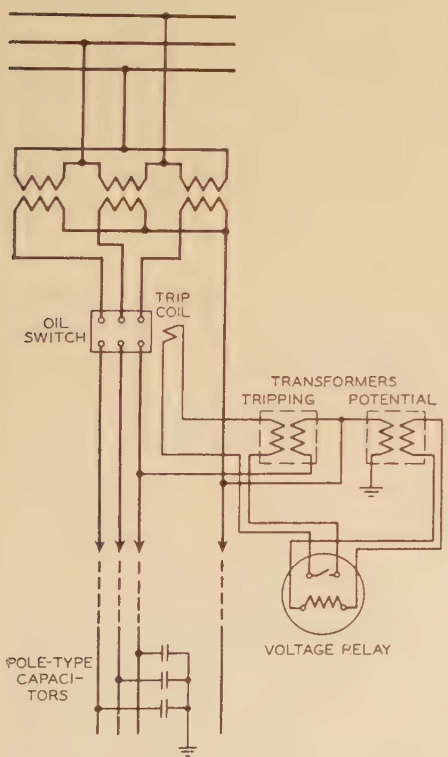
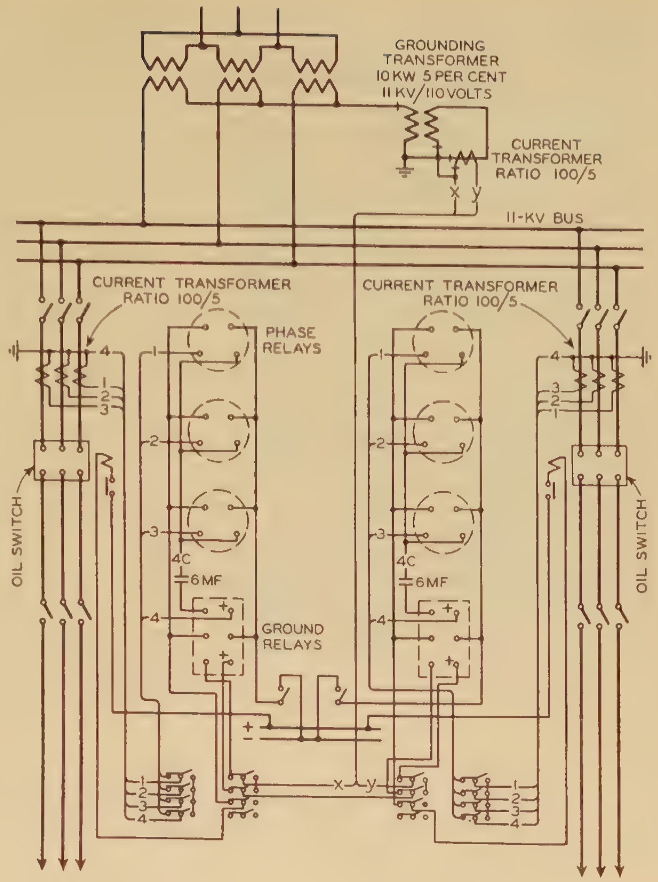


Figure 2. Sensitive ground protection for single-circuit four-wire star system

Figure 3. Sensitive ground protection for three-phase three-wire system supplying two or more feeders



for relaying the small ground faults, and at the same time means for limiting the maximum ground current to a desirable value.

In some districts where a small section is connected to a single circuit, and it is desired to clear this circuit on light ground faults, a simple scheme was devised by using an ungrounded system, and tripping was accomplished by using a voltage relay that measured zero-sequence voltage. This was tried on a 2.3-kv delta circuit approximately four miles long and proved very sensitive, using a voltage relay set at 30 volts minimum trip. In fact, when a conductor was dropped on earth or came in contact with a blade of grass, the circuit would clear without showing any signs of arcing. This scheme was too sensitive to be practical because it started tripping-out nearly every time a fog came in. In order to prevent these false operations, it was necessary to make the installation less sensitive. This was done by making the relay less sensitive; that is, giving it a higher voltage minimum trip setting, but still the operation was not satisfactory, as the leakage current from the fog was as great as the charging current from the conductors. On these circuits the smallest-size pole-type capacitors (5 kva, 2,300 volts, 60 cycles) were added at the end of the three-phase line. These three capacitors, each connected between one phase wire and ground, are sufficient to stabilize the neutral or ground point under normal conditions. By placing the capacitors at the end of the line, an added feature was accomplished; that being open-circuit protection. Should any phase wire open between the transformer bank and capacitor, the zero-sequence voltage would be sufficient to operate the relay.

Figure 1 gives a typical connection for this scheme. With the relay set at 30 volts, the grounded feeder would have to cause about 0.5 ampere to flow; so, with this arrangement, the minimum trip would occur with approximately a 2,000-ohm fault.

Figure 2 gives a method of obtaining this protection on a four-wire system. In this case, all the grounds must be kept off the neutral wire. The minimum trip of the relay is approximately 20 volts.

In these two schemes, the use of the capacitors gives the circuit a small amount of reactive kilovolt-amperes, which is generally beneficial.

If the above scheme is used when two or more feeders are supplied from a bus, there is no method of giving feeder selection so it must be arranged to trip all feeders. If selection is required, it may be accomplished by the following method:

Figure 3 is a scheme for a three-phase three-wire system supplying two feeders

that will trip only the faulted feeder. The ground relay is a standard overcurrent directional type. The overcurrent elements of all ground relays are supplied from a grounding transformer. With a ground occurring on this system, heavy currents circulate through the secondary of the grounding transformer. This gives an abundance of energy for supplying the high volt-ampere burdens of the overcurrent elements of directional relays. So, in case of a grounded feeder, this transformer supplies this energy while the residual current is called upon to operate the directional contact. Since the relay is directional controlled, as shown in figure 4, it is necessary for the directional contacts to close before the overload can operate. Referring to figure 4, when current is flowing from the ground bank through the relay coil *a*, no current can flow through *b*, although it is magnetically coupled to *a*, because the circuit is opened by contacts *c;* however, should contacts *c* be closed, which would be the element will give positive closing torque on primary currents much less than one per cent of primary rating of wound-type current transformers. This means that with a 100 to 5 wound-type current transformer, the directional element will close with less than one ampere primary current. This being the result of many tests on various voltage circuits, gave us a definite factor of safety by using the rule that minimum trip of the relays should be one per cent of the wound-type current transformer rating. In order to get the relay to trip on this value, it will be necessary to have the current transformer in the secondary of the grounding transformer of such a ratio as to give 5 amperes in the normal relay with 4- to 15-ampere taps set on the 5-ampere tap. Then, on a system with the feeder current transformers rated 100/5 and a standard distribution transformer rated 11 kv to 110 volts for the grounding bank, the current flowing in the secondary of the grounding transformer will be 100 amperes with one it is easy to figure out the size of the grounding transformer. If we use a standard 10-kw 11-kv transformer with an impedance of five per cent, the maximum current flowing to a solid ground at the station will be 10.5 amperes. It is not essential to get exactly this value, and when a four per cent transformer is used, the maximum ground current will be approximately 13 amperes.

If the power transformer bank has a delta connection, it will be necessary to use three transformers connected star, 11 kv neutral grounded, with the secondaries connected in delta, and proper current transformer used to give the one-ampere minimum trip, and the size and impedance to give the maximum ground current of approximately ten amperes. This one-ampere minimum trip represents a fault with approximately 5,700 ohms. At our Goldtown substation, the connection is the same as figure 3, except there are three feeders instead of two. After the installation, tests were made by

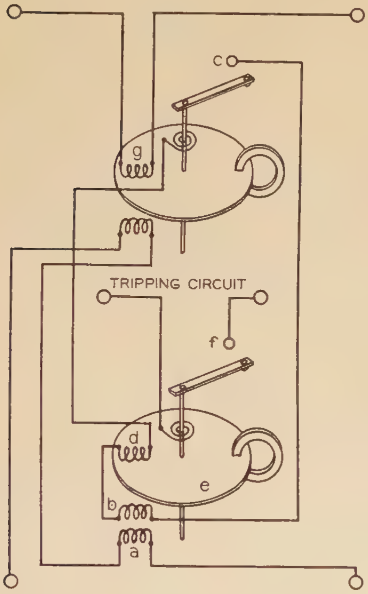


Figure 4 (left). Direction-control ground relay

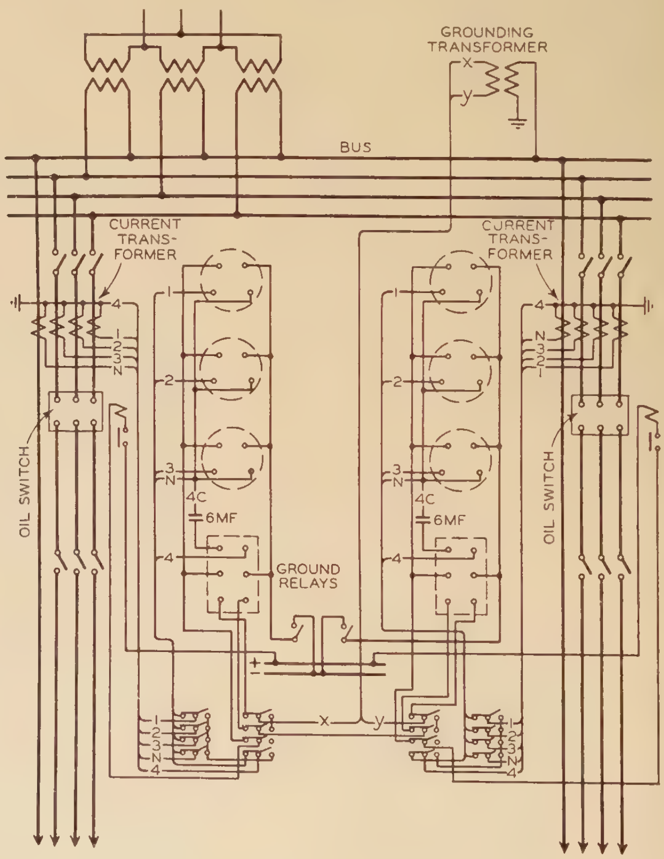


Figure 5. Sensitive ground protection for three-phase four-wire system supplying two or more feeders

case should the ground fault be on the line to which this relay is connected, then with contacts *c* closed, induced voltage from coil *b* would circulate through coil *d*. This causes rotating flux on disks *e*, closing tripping contacts *f*.

The relay used is a standard power-directional relay, and the small residual current from the line current transformers is applied to the potential coil of the directional element. A six-microfarad capacitor placed in series with the coil *g* resonates at 50 cycles and reduces the impedance of the circuit, so that the directional element will operate on a very small residual current.

In fact, from our tests, the directional ampere ground. With the 100 amperes, it will be necessary to use a 100/5 current transformer in this location, as shown. With one-ampere primary-current minimum trip, a maximum current of approximately 10 amperes would make a good ratio for relaying. By neglecting the impedance of the power bank and system, dropping a conductor on dry earth and in brush. When the conductor was lowered in the tops of brush, the current was below minimum trip, but as it was lowered further into the brush, near earth the circuit relayed. Then the conductor was dropped into a small tree, but was kept clear of earth. In this case no relay

action took place. The conductor was then dropped on earth in many places, either slowly or suddenly, and in every case the circuit relayed correctly. The values of ground current ranged from 2 to 8 amperes. The conductor was then solidly grounded, and the maximum current was approximately 13 amperes. The grounding transformer used at Goldtown is a 10 kw, four per cent.

Figure 5 shows the connections of a three-phase four-wire system. Since the load may be connected between one phase wire and neutral, it is very likely to have an unbalanced load with the neutral carrying current. For this sensitive ground-current system to function properly, it is necessary to have four current transformers and to have the neutral wire ungrounded and not interconnected. In this case, the residual of the four current transformers is a true measure of phase-to-ground current.

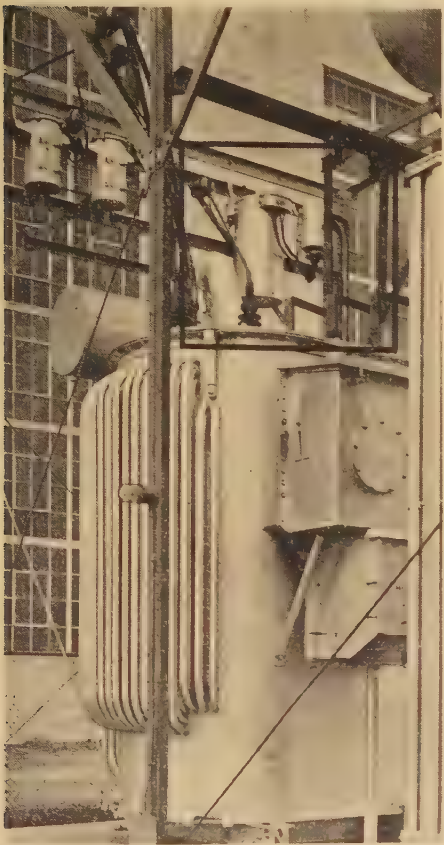


Figure 6. Grounding transformer

Figure 5 is similar to a four-wire four-kilovolt system installed at Topango substation. This installation was given a complete test by grounding feeders. The minimum trip was slightly less than one ampere. The bare conductor was pulled over trees with no relay operation, showing tree grounds would not cause unnecessary operations. The conductor was dropped on various kinds of soil, and relayed in most all cases except when dropped on very dry soil and on oiled pavement. Several cases where the low-voltage ohmmeter showed very high fault resistance, the circuit relayed when energized. One of these cases was a heavy retaining fence with several concrete poles connected together with several strands of heavy steel cable. The steel was not grounded, but was tied together. The low-voltage ohmmeter gave a resistance to ground for this installation of 40,000 ohms, yet when contacted by a conductor, the circuit relayed properly. This test confirms there must be some phenomenon of breakdown, as the minimum trip of this circuit was in the order of 2,000 ohms.

At Vernon City plant, there are 20 seven-kilovolt circuits equipped with this sensitive ground protection. This sensitive ground protection was installed on account of the desirability of joint use of pole lines with the telephone company. The normal minimum trip of each feeder was set at 600 amperes and with the possibility of several thousand amperes maximum ground fault current. With the sensitive ground protection in with 400/5 wound-type current transformers, the minimum trip is 4 amperes, and the maximum ground fault current is 40 amperes. Figure 6 shows the 20-kw, four per cent transformer used for the grounding transformer at the Vernon City plant. Figure 7 shows the installation of eight sets of feeder relays at this station; the four upper relays are the ground relays, while the corresponding three-phase overcurrent relays are directly below.

Line-dropping tests of this installation proved to be as designed; that is, the directional element gave definite operating torque on only the faulted feeder at about one-half minimum trip of four amperes, with a maximum of 38 amperes ground current.

This system of ground protection has been in operation for several years, and no unnecessary trip-outs have occurred, and many necessary trip-outs have occurred correctly. When phase-to-ground faults occur on this system, the customary voltage drop does not occur, due to the small amount of ground current flowing.

In fact, this system has proved so successful that several other installations are being made this year. Also, a system will be worked out using this principle for isolation of loop feeders during the year. At present there seems to be no means of adequately isolating phase-to-ground faults on distribution loops or interconnected systems. So, it is hoped that this system will prove as satisfactory as the one for radial feeders.

Figure 7. Ground-relay installation

Reference

1. Some Recent Relay Developments, Lloyd F. Hunt and A. A. Kroneberg. Electrical Engineering (AIEE Transactions), April, 1934.

Discussion

L. F. Kennedy (General Electric Company, Schenectady, N. Y.): For many years the detection of high-impedance grounds occurring on relatively low-voltage circuits has been one of the unsolved problems. Some have thought to avoid the problem by the use of an isolated-neutral system. Messrs. Hunt and Vivian have pointed out that continued operation of an accidentally grounded circuit may constitute a danger to life and property. The authors' approach to the problem has been to provide a grounded-neutral system having relatively high neutral impedance. With such a system the effect of resistance at the point of fault is decreased and the range of current over which the protective relays must operate is considerably narrowed down. If the working range is relatively small, it will be easier to provide a protective relay system which may be more generally relied upon to detect faults. In general, it may be said that the authors are proposing a system having a maximum zero-sequence current of the general order of ten per cent of the circuit rating. With this system they propose a relay sensitivity of one per cent. Such an operating range of the order of ten to one is not particularly difficult to obtain with existing relay designs. The greatest difficulty lies in obtaining a relay which will

actually operate at one per cent of the circuit-rating primary values. The circuit arrangement used by the authors obtains the main energy required for the operation of the relay system not from the line current transformers but from the current transformers carrying only the ground current. In this way the difficulty of obtaining very sensitive operation is overcome.

In other words, the authors are using standard equipment with impedances coordinated with the circuit rating and a modified system of relay connections. They have furthermore differentiated between the various types of circuits used for distribution service and apply solutions all of the same general class, but specifically adopted to each type of service.

In the early part of the paper under the heading "Ground Faults," the authors quote figures on various tests which were made under grounding conditions where relatively small currents were measured. The value of these test figures would be much greater if they were presented together with the actual constants of the circuit on which the tests were made. The general statements as to the amount of current which might flow through various types of soil would be of much greater value if related directly to maximum currents which would be encountered with a fault having zero resistance. More data of this type, together with a résumé of operating experience as times goes on, would be greatly appreciated by all who are interested in the solution of this particular problem.

Wm. R. Brownlee (The Commonwealth and Southern Corporation, Jackson, Mich.): In view of the tremendous increase in common-neutral distribution construction during the past six or eight years, it is unfortunate that the various methods of sensitive ground protection described by the authors are not recommended except for delta circuits or four-wire circuits with individual neutral wires grounded at the supply substation only. Many schemes have been available for years for securing sensitive ground protection on delta or unigrounded systems. However, the choice of sensitivity is practically always a compromise between conflicting requirements so that in the vast majority of installations, relay settings are less sensitive than the minimum which is readily available with standard equipment.

The authors are to be congratulated on the ingenious use of distribution transformers and current transformers, which are normally carried in stock, as a makeshift arrangement for securing a neutral reactor of some 600 ohms and a very low ratio or even step-up current transformer. If, after further experience, they should decide that they wish to maintain the extreme sensitivity and rather low upper limit of fault current, it might be well to investigate the cost of simple neutral reactors and step-up current transformers which might be less than that of the distribution transformer combination, even though the latter is a quantity-production unit.

Many methods are generally available for securing sensitivity on the order of one ampere primary as recommended by the authors. For single circuits, a standard 5/5-ampere neutral-current transformer may be used with a standard 0.5- to 2.5-ampere relay. For a simple residual connection, standard relays are available with a minimum rating of 0.1 ampere with which a pick-up of one ampere primary can be secured with line current transformers up to 50/5 amperes which would ordinarily be associated with a 1,000-kva circuit at 11 kv. Another common method is the use of a current-polarized directional ground relay having most of its volt-ampere burden concentrated in the coil supplied from the neutral current transformer, permitting low current settings even on circuits above 15 kv where bushing current transformers are frequently used. With instrument-type current transformers, the low burden of such a relay permits the use of a step-up current transformer for the current supplied from the residual of three line current transformers, allowing most any desired sensitivity to be obtained with standard relays.

Where special considerations may warrant extreme sensitivity, an arrangement was described in 1933[1] for responding to grounds with as much as 5,000 ohms resistance on a 2.3-kv three-phase circuit. The measured values in a variety of conditions at this voltage varied from 60 ohms to 3,300 ohms at point of contact.

The use of neutral impedance in limiting ground current has been widely discussed.[2] It is felt that the maximum value of ten amperes recommended by the authors is far too low for the usual conditions to give any appreciable consideration to the selectivity of branched fuses, individual distribution transformer fuses, or the ability to clear defective lightning arresters from the line or even to cause sufficient damage on them (or on other defective apparatus) to permit locating and clearing permanent trouble in any reasonable length of time. With these considerations in mind, the maximum current should probably be not less than 50 to 100 amperes.

Undoubtedly the schemes of the authors are useful in combating local conditions. They are faced with unfortunate California weather conditions, such as extreme drought resulting in heavy layers of dust contrasted with the occurrence of fogs sufficiently dense to short circuit the charging current on one conductor of a circuit.

References

1. Zero-Sequence Current Transformers for Ground Protection, J. W. Graff. *Electrical World*, December 23, 1933, page 82.

2. General Considerations in the Use of Neutral Impedance, EEI Publication No. *D*-14.

P. E. Benner (General Electric Company, Schenectady, N. Y.): The authors are to be congratulated on their analysis and solution of the problem of de-energizing of grounded conductors. With the stretching out of circuits to pick up scattered loads, situations involving this problem of fault protection are apt to turn up on any system. There is also an increasing appreciation of the necessity for providing a means of de-energizing grounded or faulted conductors to minimize possible danger to life and property.

The common-neutral multigrounded system depends on short-circuit currents for de-energizing grounded conductors and in this way is dependent to a large degree on low ground impedance for successful operation. Unfortunately, as the authors point out, the ground and contact resistance may be almost anything with the result that de-energizing grounded feeders is somewhat uncertain with this type of protection.

In a common-neutral multigrounded system where sufficient ground current is obtained in the case of grounded conductor to cause the operation of a sectionalizing device or the substation breaker, this method of protection might possibly have the advantage of confining the outage to a fewer number of customers; however, it is doubtful whether this advantage would offset the more positive operation of the protective scheme described by the authors. In this connection it probably would not be entirely unexpected if the de-energizing of grounded feeders assumed a greater importance in future layouts than first cost or service reliability because of the fact, as mentioned by the authors, that it involves the question of danger to life and property.

In urban areas where water-pipe grounds are available, the common-neutral multigrounded systems would probably be entirely effective in isolating grounded feeders. Just how effective the multigrounded common-neutral system is for isolating grounded feeders in rural areas will unquestionably be determined in the next few years by the experience with the many miles of this type of circuit which have been recently installed. In any event, it is believed it will be advisable to keep a close check on this phase of circuit operation so that proper value can be placed on this question of providing for the de-energizing of grounded feeders on future circuits.

Frederick C. Lindvall (California Institute of Technology, Pasadena): The need for sensitive ground protection is brought out by Messrs. Hunt and Vivian through examples of peculiar grounding conditions experienced on the Southern California Edison system. In these examples the ground current either failed to flow altogether, or else was of much smaller magnitude than would have been predicted on the basis of ordinary resistivity measurements.

Verification of these experiences has been made at the California Institute of Technology both with samples of earth brought into the laboratory for study and with actual high-voltage grounds in soil outside the high-voltage laboratory.

It was found that a wire or small electrode lying on the surface of moderately dry ground could be held at a potential of 10,000 to 15,000 volts without breakdown or flow of appreciable ground current. Actual ground current flow was found to be the result of a breakdown of the soil quite similar to that of dielectric failure. Broadly summarized, the results indicate that dry to moderately dry soil should be regarded more nearly as a poor dielectric material than as a substance of definite resistivity. The laboratory studies indicated that moisture content of the soil, its composition, and the mode of contact of the electrode all have a bearing on the subsequent breakdown and flow of ground current. The wide variation of the results points to the desirability of field studies comparable with actual operating conditions rather than an intensive laboratory study of the dielectric behavior

of soils, although such investigation would offer results of considerable academic interest.

Our conclusion is that a careful study of grounding conditions should be made, as the results of Hunt's and Vivian's work, together with the laboratory studies which we have made, indicate considerable uncertainty in the technique of grounds, both deliberate and accidental.

J. R. North (The Commonwealth and Southern Corporation, Jackson, Mich.): This paper describes a unique method of obtaining sensitive ground relaying on three-phase delta (ungrounded) circuits or three-phase unigrounded circuits. This method of very sensitive relaying is no doubt advantageous, as described by the authors, in areas where the fault energy and duration must be held to extremely low values.

In the introduction, it is stated that one of the reasons for providing ground relaying on distribution circuits is "to permit joint use of pole lines with the telephone companies." It is difficult to understand just why such sensitive ground relaying is required for joint use with low-voltage distribution circuits, since there are many thousands of miles of jointly used pole lines throughout the country now operating apparently satisfactorily with distribution circuits which are not provided with ground relaying.

In the case of high-voltage joint use, detailed studies have indicated that the conditions as far as the power circuits are concerned would be properly met if the circuits are promptly de-energized in, say, five seconds or less with fault currents of the order of 50 amperes or more. Contacts with communication circuits generally result in values of fault impedance far less than in the case of a contact with dry dust and thus ample current would be available for operating ground relays or blowing fuses.

M. A. Sawyer (Southern California Telephone Company, Los Angeles): The methods of obtaining sensitive ground protection on radial distribution feeders described by Messrs. Hunt and Vivian appear to be admirably suited for use in situations involving the joint use of poles by higher-voltage power distribution circuits and communication facilities. As has been pointed out in a previous paper ("Protection Features for the Joint Use of Wood Poles Carrying Communication Circuits and Power Distribution Circuits Above 5,000 Volts," J. O'R. Coleman and A. H. Schirmer, AIEE Transactions, March 1938), safety in joint use is dependent largely on the following factors:

1. Frequency of occurrence of contacts between power and telephone circuits.
2. Voltage on the telephone plant when contact occurs.
3. Current in the telephone plant when contact occurs.
4. Duration of contact.

The first factor is, of course, in many respects a function of the mechanical design, construction, and maintenance of the line and depends somewhat on the type of plant, tree conditions, exposure to traffic, or other hazards rather than the electrical characteristics or protective devices. The other three factors are, however, controlled to a large extent by the system of sensitive ground protection described in the paper. In addition to providing a means of promptly de-energizing the feeder in case of accidental contact with telephone plant, the voltages and currents impressed on the

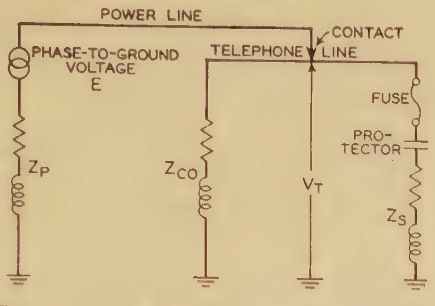


Figure 1. Fault circuit of a power-line contact with telephone plant

telephone plant are minimized by virtue of the large amount of impedance introduced in the power system by the grounding transformer.

The voltage on the telephone plant in case of contact is dependent on the power-circuit voltage and the ratio of the impedance in the telephone plant between the point of contact and ground to the total impedance of the fault circuit. Referring to figure 1 of this discussion which shows in schematic form the fault circuit of a grounded-neutral system, it will be noted that the voltage on the telephone plant (V_t) is $E\frac{Z_t}{Z_t+Z_p}$ where Z_t is the parallel impedance of the two paths to ground. The current in the telephone plant is $\frac{E}{Z_t+Z_p}$ and divides over the two paths inversely in proportion to the impedance of the paths. If the telephone fuse opens, the voltage across the fuse and on the telephone plant then becomes $E\frac{Z_{co}}{Z_{co}+Z_p}$ and the current is $\frac{E}{Z_{co}+Z_p}$. If the telephone fuse opens and the connection toward the central office is lost at the point of contact, the voltage across the fuse and on the telephone plant then becomes E. Since the current under these conditions becomes zero, the power circuit would not be de-energized and this voltage would remain on the telephone plant unless it was large enough to break down the insulation at some point.

Since the sensitive ground protection system for use on higher-voltage feeders employs a grounding transformer in the neutral the impedance of the power system (Z_p) is increased by an amount equal to the impedance of this transformer. If, for example, a ten-kilowatt 11-kv grounding transformer of five per cent impedance is used the added impedance would be approximately 605 ohms. This would limit the fault current that could flow into the telephone plant in case of contact to a maximum of about 10.5 amperes assuming $Z_t=0$ and neglecting the impedance of the power feeder. If it is also assumed that the impedances of the two paths to ground in the telephone plant are $Z_{co}=200$ ohms and $Z_s = 50$ ohms (resistance) and again neglecting the impedance of the power feeder the total current would still be approximately 10.5 amperes and the voltage on the telephone plant would be about 420 volts. If the telephone fuse operates the current would be reduced to about 10 amperes and the voltage on the telephone plant would increase to approximately 2,000 volts. If in this case the minimum trip current of the feeder ground relay is 2 amperes it is quite probable that the circuit will be de-energized before the telephone fuse will operate.

Where the telephone plant is cable the impedance to ground (Z_{co}) will normally be very small as compared to the impedance of the grounding transformer. A contact with the cable will therefore impress a relatively low voltage on the telephone plant, well within the range that can be handled by the telephone protector. Furthermore, with the small value of fault current the liability of a cable burn-off allowing the voltage on the telephone plant to rise to full phase-to-ground voltage is remote. It therefore appears that with this system of ground protection and with the normal cable sheath grounding and subscriber station protection practices employed in the telephone system, suitable protection co-ordination should be obtained where higher-voltage joint use with telephone cable is involved.

Where the telephone plant is largely aerial wire it is normally difficult to obtain protection co-ordination of the two systems because of the relatively high impedance of the telephone wire, and in many instances in rural areas low-impedance grounds are not available for the subscribers' protector. Due to the high impedance in the telephone plant the resulting voltages on the telephone plant will be high and the power system fault current may be limited to the extent that the circuit is not promptly de-energized. Furthermore, with the limited current-carrying capacity of the open wire as compared to the cable sheath and suspension strand, the possibility of burning off the wire is much greater than where cable plant is involved.

However, with the method of ground protection described in the paper the fault current may be limited to a relatively low value which in turn reduces the possibility of burning off the telephone open wire. Also, because of the impedance of the grounding transformer the impedance to ground of the telephone plant may be somewhat higher than would otherwise be permissible without impressing an excessive voltage on the telephone plant at the time of contact. Since the relay system may be arranged to de-energize the feeder with a fault contact resistance as high as 2,000 or 3,000 ohms it is unlikely that the impedance of the open-wire telephone plant assuming no burn-offs will prevent tripping of the circuit. With the use of auxiliary three-kilovolt protective gaps to ground in the telephone plant to limit the voltage across the fuse and to insure a continuous path to ground for the contact current, it appears that with this method of ground protection employed in the power system, protection co-ordination can often be secured in a practicable manner in open-wire joint-use situations.

While the sensitive ground protection described in the paper was originally developed to enable the tripping of distribution circuits involved in ground faults of high con-

tact resistance it would appear to also offer a practicable means of providing the necessary degree of safety in many situations in which higher voltage joint use is the best solution. The authors are to be complimented on their development of this system and its application as described in the paper.

R. M. Smith (Westinghouse Electric and Manufacturing Company, Newark, N. J.): Mr. Hunt and Mr. Vivian are to be congratulated on the amount of field development work that they have done on this problem. The solution which they offer is certainly a simple one and from their records it appears that a sensitive-type ground protection has been achieved without incurring unnecessary trip-outs. It would be desirable to hear from other relay engineers in different parts of the country with respect to their experience in attempting to achieve a sensitive type of protection.

A recent investigation undertaken by the writer indicated that although a few attempts had been made to obtain ground-fault relaying on distribution feeders with a sensitivity as low as 5 amperes primary, the general trend was toward considerably higher currents usually with a minimum of 50 amperes. The writer believes that the danger of unnecessary trip-outs due to tree grounds has been greatly exaggerated and that no real concrete data exist as to the extent of the hazard. It is unfortunate that the novel solution offered by Messrs. Hunt and Vivian is applicable only to distribution systems operating with a single ground. The general tendency at the present time appears to be in the opposite direction; that is, multiple grounds. Perhaps it might be well for the industry to again evaluate the many factors that are involved in single versus multiple grounding and reverse this trend, if the advantages of a sensitive ground protection overweigh some of the advantages of the multiple-grounded system.

L. N. Crichton (Westinghouse Electric and Manufacturing Company, Newark, N. J.): It is my belief that this paper gives the answer to the old problem of properly protecting distribution circuits against the hazard due to fallen wires. The simplicity of the idea is unusual; it requires a standard relay and a standard distribution transformer as a grounding reactor. The requirements as laid down for proper sectionalizing are likewise simple; namely, to clear all troubles having a ground current of more than one ampere. The amount of unbalance current in the load does not enter into the problem. The method of determining the size of the ground transformer is simple and thoroughly explained in the paper.

It is to be hoped that other systems in different localities will quickly install this type of protection so as to obtain experience in parts of our country where climatic conditions are different. What we all suspect, of course, is that in most localities, tree ground currents will be a nuisance after long spells of wet weather.

Recent tests that have been made in another part of the United States indicate that tree grounds are not so likely to cause trouble as has been feared in the past. Perhaps it will be necessary to raise the minimum current to some value above the one ampere set by the authors, but the practical value may not be more than two, three, or four amperes. I am confident that the limit will be a low one and hope that the industry will soon discover what it is by a number of trials of this new scheme.

Lloyd F. Hunt and **J. H. Vivian:** We appreciate very much the interest shown in our paper, and wish to thank our friends who have contributed by their discussions.

Mr. Kennedy has brought out the necessity of having more information on "Ground Faults." We admit we have been lax in gathering every bit of information regarding the detail circuit constants and actual range of possible current in some of the tests. We purposely left this information brief for two reasons: first, it only applies to our conditions; and second, as Doctor Lindvall has brought out in his discussion, a very great deal is not known about earth faults and earth contact resistances, so we feel that this subject is important enough to have considerable more work done on it and a paper written covering the results; Mr. Kennedy also brings out the desirability of having operating experience. To date our operation has been all correct. However, with more experience and with this type of protection in more varied localities, it will be possible to give valuable information on its operating record.

Mr. Benner brings out a very interesting part of the story of sensitive ground protection that we purposely avoided, which is the policy of de-energizing grounded feeders. Each organization has its problem in this regard, and may make its own decisions whether or not grounded feeders should be left in service.

It is our desire to have sufficient installations to determine by experience how far we can justify this type of protection. We are now cutting over one urban territory, from 2.3 kv delta to 4 kv four-wire, to this type of sensitive ground protection. The normal change would be to 4 kv four-wire multigrounded neutral system; however, with this change it will be possible to gather interesting operating experience.

We feel, as Mr. Benner does, that with the many miles of rural lines now being put into use, more consideration should be given this problem of de-energizing them in the case of grounded conditions.

Mr. Brownlee has reviewed the prior methods of sensitive ground protection, but in his treatise no attempt has been shown to limit the ground current, which feature we feel is very desirable. In his case of using a 5/5 current transformer with one ampere tap relay, if solidly grounded on a 3,000-kva single 11-kv circuit, the relay would have approximately one ampere minimum trip, but also would give approximately 500 amperes maximum current, or a range of 500 to 1. Most every relay engineer will recognize that this range is impossible. This is more or less true in other examples brought out by Mr. Brownlee. If his method were used on the 7-kv system mentioned in the paper, it would have a minimum trip of approximately 55 amperes. This would make it necessary to use a very much more expensive joint pole construction. The saving from using the simpler construction would many times pay for the installation of our type of ground protection.

In this day of changes, the relay engineers are finally "evoluting" to a place where they can use some standard equipment, such as standard transformers for makeshift (manufacturers please note) grounding bank. All of this equipment is usable material, should further changes be made. If our present 600-ampere grounding banks were composed of standard distribution transformers instead of zig-zag, we could get some use out of them now instead of placing them in the discard. Therefore, from these experiences, we feel it is much better to use standard devices that can later be used for other purposes.

Mr. North has brought out the question of joint use with the telephone companies. We wish to bring out again that this system was developed for other reasons than joint use, but when we were confronted with joint use, especially on higher voltages, these systems of protection were available, and allowed us to use a much cheaper construction than normally used for this service, the saving being more than adequate to justify its use.

Doctor Lindvall and his associates have started a very important phase of this work of determining the phenomena regarding earth contact resistance and breakdown value. We hope he may continue his investigations, which will give us all much valuable information.

Mr. Sawyer's discussion gives in detail the advantages of our type of protection when used in joint pole arrangement. We feel that, by working with Mr. Sawyer on these problems, much better service can be rendered the telephone subscribers, who are also our customers, and at the same time more economical methods of distributing both services can be developed.

Mr. Smith brings out the unfortunate fact that this protection cannot be used on multigrounded systems. This is true, and the changing from multigrounded uninsulated-neutral systems would be expensive, and would cause a considerable write off of certain features of old construction. However, in the changeover mentioned before, a study is being made to establish the difference in actual relative costs when a new job is made.

Mr. Crichton has brought out the problem of tree grounds; also, Mr. Smith mentioned this subject. Dry trees will not cause this protection to operate when the very low minimum trip is used. It is possible that trees will cause actual phase-to-phase contacts by wind which will relay the line. In the case of wet trees, the earth must also be wet, so earth contacts would then be of less resistance. In this case it would be possible to design the system for higher minimum trip and, by taking advantage of the range of tap settings of the relays (normally 4 to 15 amperes), adjustments could be made as desired. We have had no experience with the relation of dry trees to wet trees, as compared to dry earth to wet earth, but it could be expected that the same degree of discrimination could be obtained during the wet seasons. In several cases our practice is to make the ground protection less sensitive during the rainy season.

Again we wish to express our appreciation to those who have taken part in this very interesting subject.

Transient and Steady-State Performance of Potential Devices

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THE increasing use of high-speed relaying with the resulting emphasis on the transient performance of potential devices has led to an extensive analysis of their performance under transient conditions. Both analytical and network-calculator methods have been developed for predetermining transient performance. Tests have been made to substantiate the methods of analysis and to show the character of the transient and extent of control in typical cases. Novel means have, likewise, been devised for presenting the steady-state performance of the device. In particular, the introduction of the equivalent circuit of the device represents an important advance in the visualization, both of the transient and steady-state performance. In this paper, after a brief description of circuit arrangements of the potential devices under discussion, the new theoretical methods are presented, followed by the substantiating test information.

Circuit Arrangements

A potential device may be energized from a condenser bushing or from a coupling capacitor, which may be represented as a capacitance potentiometer as illustrated in figure 1. The upper section is identified as the stack capacity and the lower section as the tap capacity. The intermediate point is called the tap. Both the stack and tap sections are contained within the porcelain housing of the bushing or capacitor.

Figure 1 shows three circuit arrangements of commercial devices and also illustrates required modifications in capacitor devices for use with carrier. Means are provided for neutralizing the effective series capacitance of the source by series reactance between the source and the burden. Variable reactor and capacitor are used in (*a*); transformer reactance in (*b*), (*c*), and (*d*). The circuit of figure 1*a* is used in the bushing potential device and the low-capacity capacitor potential device. Circuits (*b*) and (*d*) apply to the high-capacity high-accuracy capacitor potential device and include provision for obtaining several secondary voltages simultaneously through the use of a coordinated auxiliary transformer. Both the main and auxiliary transformer are designed to operate at a low flux density and will remain stable when subjected to flux densities in excess of four times normal. The circuit of figure 1*c* is used in the simplified capacitor potential device and is essentially one in which the capacitive and inductive reactances are not variable. The secondary voltage thus obtained is substantially in phase with line-to-ground voltage of the system. Simultaneous use of the coupling capacitor as a carrier-current channel, illustrated in (*d*), requires the addition of carrier-frequency chokes to complete the fundamental-frequency circuits and permit a series relation at carrier frequency between the carrier-current set and the transmission line.

The proper device for any particular application is selected with a view to economic as well as to performance considerations. The standard capacitor potential devices have the greatest accuracy and best performance, and the simplified capacitor potential device is lower in cost.

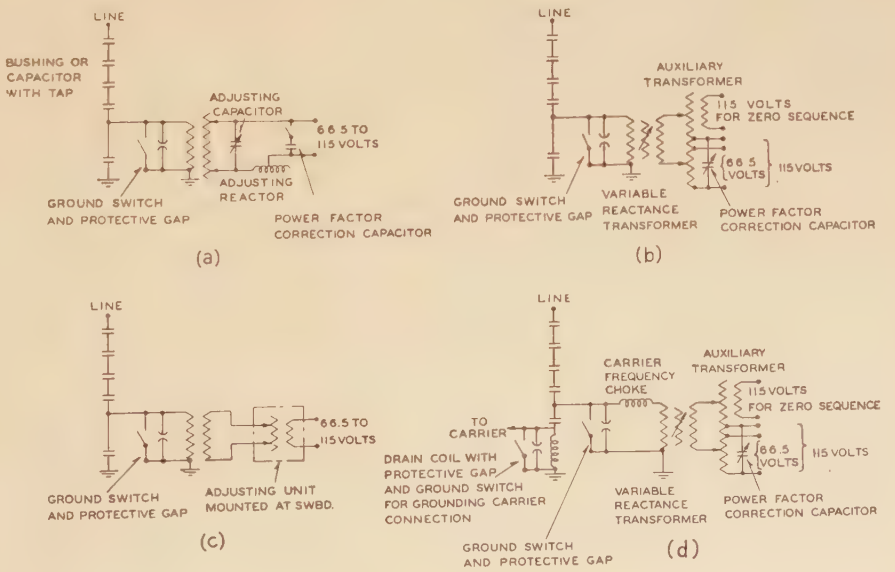
Figure 1. Circuit arrangements of potential devices

(*a*)—Bushing or capacitor device

(*b*)—High-capacity capacitor device with multiple secondary

(*c*)—Simplified capacitor device

(*d*)—High-capacity capacitor device with arrangements for carrier



Steady-State Performance

The Equivalent Circuit

The performance of a potential device may best be visualized through an understanding of its equivalent circuit, figure 2*d*. Because of the importance of a thorough understanding of this circuit in what follows, its derivation and meaning will be carefully considered at this point.

The actual circuit of a typical single-phase potential device is shown in figure 2*a*. There are many possible variations, and this particular circuit has been selected for consideration because it includes the major elements of importance and yet it is quite simple. The concepts gained from a study of it are later extended to include some of the more important variations. There is a double transformation of voltage, first through the potentiometer, formed by the "stack" and "tap" capacitances, and second through the transformer.

In figure 2*b*, the transformer is replaced by its equivalent circuit consisting of a series leakage impedance and an exciting impedance branch. The latter is almost negligible in a liberally designed transformer and the approximation of connecting it at one end of the leakage branch as shown is entirely justified. It

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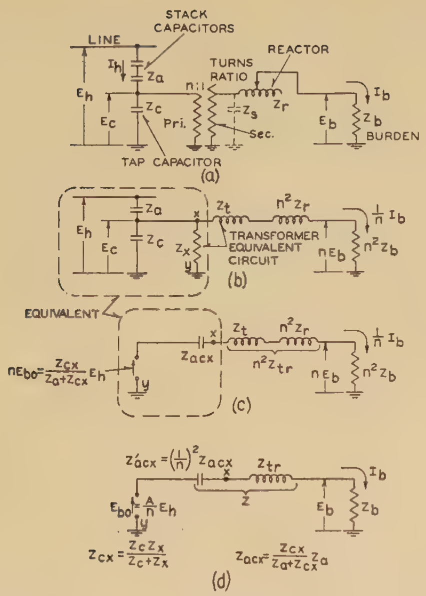


Figure 2. Actual and equivalent circuits of a device without auxiliary tuning capacity on secondary of transformer

(*a*)—Actual circuit

(*b, c, d*)—Successive equivalent circuits

may then be paralleled with the tap capacitance, and for a typical case the parallel impedance of the two is only about three per cent greater than that of the tap capacitance alone.

In figure 2*c*, the applied voltage and potentiometer circuit are replaced by a proportional applied voltage and a series impedance. This series circuit (*c*) is exactly equivalent to the potentiometer circuit (*b*) according to Thevenin's theorem of networks[5] provided the following relations are maintained. The impressed voltage in the series circuit must be the same as the voltage that would appear at the output terminals *x-y* on the potentiometer circuit at no load (burden disconnected). The impedance in the series circuit must be that which would be measured at the output terminals *x-y* of the potentiometer circuit, with the line voltage terminal short-circuited to ground and burden disconnected.

It is clear then that the impedance in the series circuit is the parallel of the stack capacitance, the tap capacitance, and the transformer exciting impedance, and consequently is essentially a capacitance. Its value is only a little greater than the tap capacitance if the stack capacitance is small, as in high-voltage devices. The combination of the series impedances in (*c*) into a single value in (*d*) is obvious.

5. For all numbered references, see list at end of paper.

If an adjusting capacitor is used on the secondary side of the transformer as shown dotted in figure 2*a*, the final equivalent circuit takes the same form (*d*). However, the values of the applied voltage and series impedance in this case are obtained by an additional transformation, using Thevenin's theorem, to take into account this capacitance (appendix I).

Performance From Vector Diagrams

The steady-state performance may now be investigated by analyzing the circuit, figure 2*d*, which is the exact equivalent of the actual potential device. Figure 3 shows a set of vector diagrams drawn for a particular device operating at rated burden. It will be observed that with unity power factor burden (figure 3*b*) the voltage across the source capacity and the inductance are equal and are approximately 80 per cent of the voltage across the burden. The voltage across the series resistance, which includes all of the device losses, amounts to 9.5 per cent of the burden voltage. From these relations, a number of interesting facts regarding the device may be deduced. The 9.5 per cent resistance drop represents the ratio regulation from no load to full load. Since the reactance drops cancel, the resistance drop constitutes the entire source voltage drop to the burden. The tap voltage, which is equal to the burden voltage added vectorially to the reactor drop, and the result multiplied by the transformer turns ratio, is higher at rated load than at no load. This is due to the fact that the reactance drops decrease to zero as the burden current is reduced to zero.

Figure 3 (*b* and *d*) also illustrates that phase-angle adjustment of the device is obtained by varying the inductive reactance. The adjustment shown in (*b*) results in zero phase angle between the high-voltage line-to-ground voltage and the burden voltage, while that in (*d*) results in a burden voltage leading by 30 degrees. The latter is obtained by decreasing the inductive-reactance drop. It is evident that with this adjustment a large phase-angle regulation as well as an increased voltage regulation results, since the voltage drop occasioned by the burden current through the complete impedance,

(*a*)—Adjustment for zero phase angle and 50 per cent leading power factor burden

(*b*)—Adjustment for zero phase angle and unity power factor burden

(*c*)—Adjustment for zero phase angle and 50 per cent lagging power factor burden

(*d*)—Adjustment for 30-degree leading phase angle, and unity power factor burden

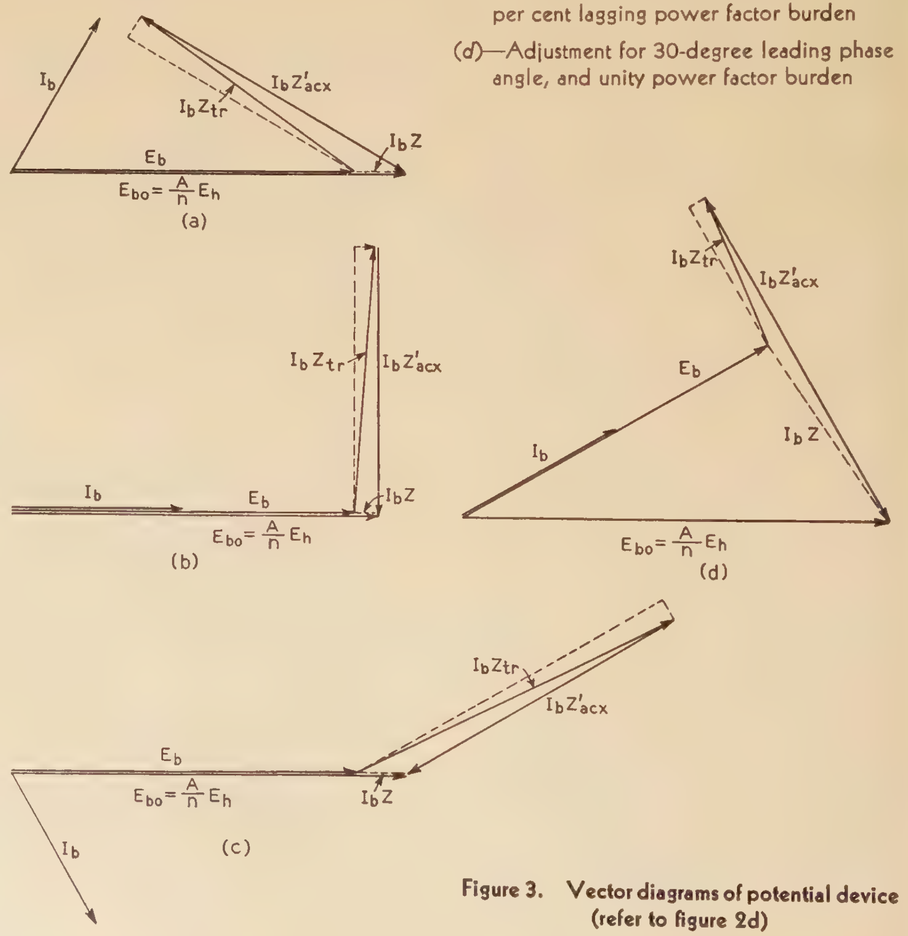


Figure 3. Vector diagrams of potential device (refer to figure 2d)

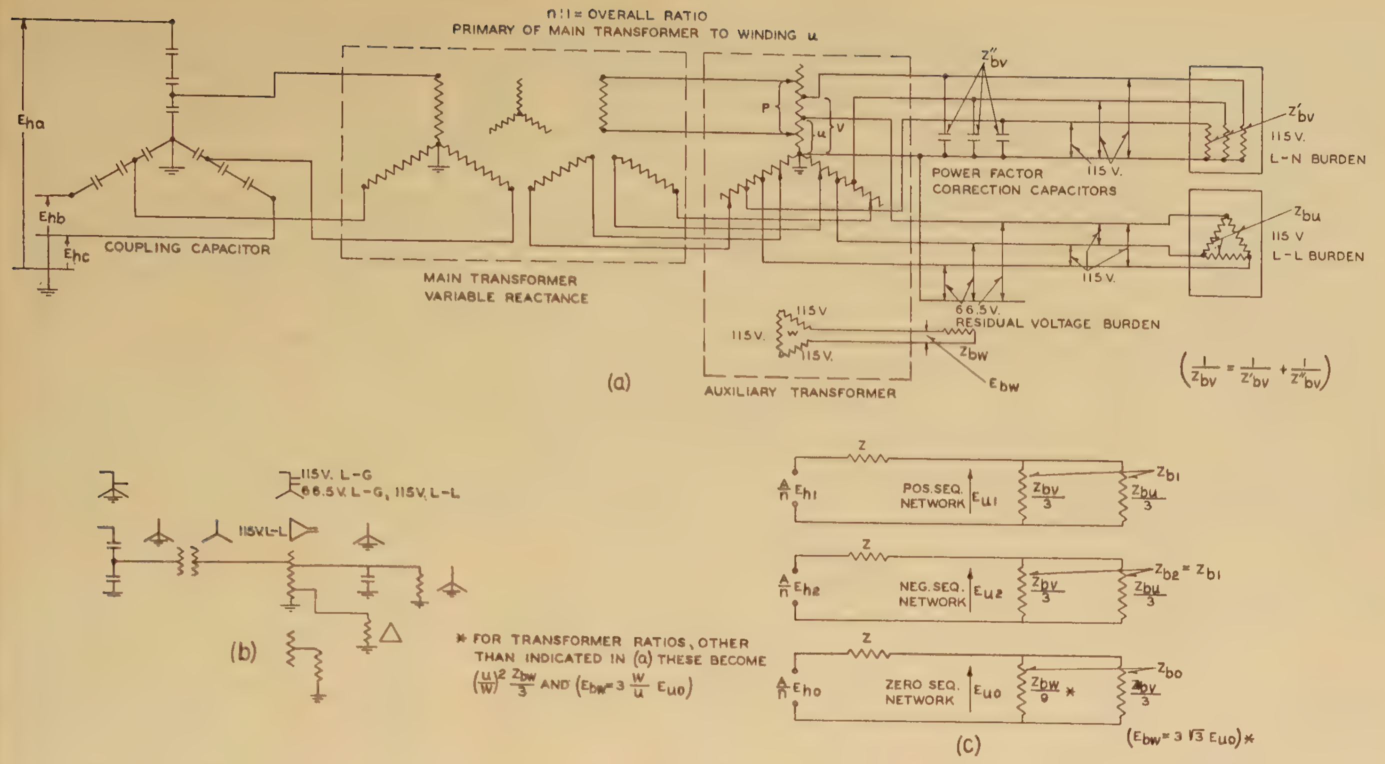


Figure 4. Equivalent burdens and sequence networks

(*a*)—Polyphase connection of potential devices with burdens on various windings of auxiliary transformers

(*b*)—Shorthand representations

(*c*)—Sequence networks

Z, decreased to zero as the burden current is reduced to zero. In fact, as the burden current becomes zero with normal line voltage, the phase-angle error becomes practically zero regardless of the angular adjustment of the device at rated burden.

Table I indicates the voltage performance and burden performance for various types of potential devices, while figure 10 illustrates the characteristic curves for two specific designs.

Symmetrical-Component Theory

The performance of potential devices having balanced three-phase connections operating under unbalanced line voltage conditions is best approached through the method of symmetrical components. This performance is defined as the over-all ratio from high-voltage line voltage to burden voltage, and includes both magnitude and phase angle. The sequence networks for a typical device and its connected burdens are outlined in figure 4, using the equivalent circuit of the single-phase potential device previously developed.

The positive- and negative-sequence performance characteristics are the same. In either case the performance is identical with that of a single-phase device supplying a burden impedance equal to the positive- (or negative-) sequence phase-to-neutral impedance of the total three-phase burden, on the particular turns base used. Thus for all three-phase and line-to-line fault conditions, involving only positive- and negative-sequence quantities, the performance characteristics of all secondary voltages are the positive-sequence performance, and are given directly by the single-phase test data.

The zero-sequence performance will in general differ from the positive-sequence performance since the zero-sequence burden impedance is different from the positive-sequence burden impedance as illustrated in (*c*). For fault conditions involving zero-sequence the residual performance is identical with zero-sequence performance, so that single-phase tests using the burden impedances indicated in the zero-sequence network apply. The residual burden voltage is related to the zero-sequence burden voltage by the factor $3\sqrt{3}$ for the transformer ratios of figure 4. These statements are made on the basis of the equivalent circuit which assumes all impedances are linear and consequently does not include minor effects due to variation of transformer exciting impedance. The line-to-ground performance is a function of both positive- and zero-sequence performances and is expressed mathematically in appendix II.

Where residual voltage only is required, a single device may be used and its zero-sequence performance is the same as its single-phase performance with the three capacitors paralleled at tap and line terminals. The burden rating of such a device refers to the burden on the second-

Table I. Potential-Device Performance Data

	Voltage Performance (a)		Burden Performance (b)	
Type of Potential Device	Ratio Error (Per Cent)	Phase-Angle Error (Deg)	Ratio Error (Per Cent)	Phase-Angle Error (Deg)
Low-capacity bushing device	20	30	35	5
High-capacity bushing device	8	10	20	5
Low-capacity capacitor device	5	5	15	4
High-capacity capacitor device	4	4	10	2
Simplified capacitor device	5	15	35	15

These values indicate: (*a*) The maximum errors to be expected with changes in line voltage of 5 per cent to 120 per cent of rated voltage with the device adjusted for rated watt burden at 66.5 volts, 60 cycles, and rated line-to-ground voltage. (*b*) The maximum errors to be expected with changes in burden of 0 per cent to 100 per cent of rated watt burden when energized at rated line-to-ground voltage, and with the device adjusted, for rated watt burden at 66.5 volts 60 cycles.

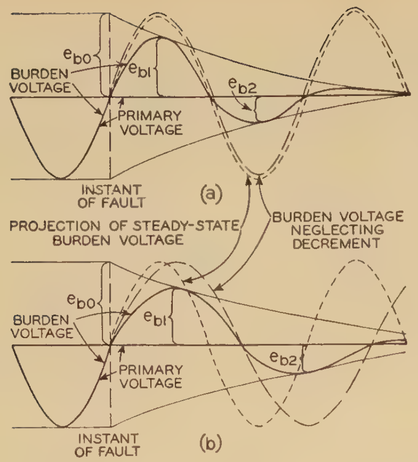


Figure 5. Potential-device transients

(*a*)—Natural frequency equal to system frequency

(*b*)—Natural frequency less than system frequency

ary terminals at rated voltage when zero-sequence voltage is applied at the line terminals. The required ratio from line zero-sequence voltage to burden voltage, in any case, is dependent on system grounding characteristics and is determined in the same manner as the ratio of star-series auxiliary transformers.

Figure 6. Single-phase transient tests for high-capacity 230-kv bushing potential device

Primary line-to-ground voltage 127 kv, 60 cycles; secondary voltage 63.5 volts

A—Timing wave
B—Secondary voltage
C—Primary voltage

(*a*)—Secondary burden 10 volt-amperes—100 per cent power factor

(*b*)—Secondary burden 40 volt-amperes—100 per cent power factor

(*c*)—Secondary burden 100 volt-amperes—100 per cent power factor

Transients—Theory

When a fault occurs there is a lag between the decrease of line voltage to a new level and the time the secondary voltage of the device reaches its corresponding new level, the extent of this lag depending on the network and burden constants. During this time the secondary voltage deviates from its correct value. This difference is in the nature of a damped wave which may be oscillatory or "dead beat" and its importance depends upon the application involved. In the case of a high-speed directional relay, the transient may be of assistance to good relay operation provided the phase shift is small. However, if high-speed impedance relays are used, it becomes desirable to reduce the transient to a value which will not materially extend the relay operating time.

Transient Performance—Series Circuit

The vector diagrams, figure 3, throw considerable light on the transient performance of the potential device. The equivalent circuit, figure 2*d*, derived for steady-state conditions applies also to transient conditions if the transformer magnetizing branch is neglected. The burden which was lumped as a single impedance for the steady-state conditions must be segregated into its actual components for correct analysis of the transient conditions. For example, a pure watt burden consisting of a resistor will have entirely different characteristics under transient conditions, than a lagging-power-factor burden, corrected to unity power factor by a capacitor.

Consider first a pure resistance burden equal to the device rating and the device adjusted for zero-phase angle error. The steady-state proportions, indicated in figure 3*b*, are approximately 1.1, 0.8, and 0.8 for resistance, inductive reactance, and capacitive reactance, respectively. This circuit, therefore, has a natural frequency equal to the normal system frequency. The transient is nonoscillatory or oscillatory depending on whether R^2 is greater than $4X_LX_C$ as shown in appendix III. From the impedance proportions of the vector diagram, it is apparent that the circuit is oscillatory having a logarithmic decrement of 11.5 per cent, that is, the ratio of successive half cycle peaks is 11.5 per cent for the decaying transient voltage. The most severe transient occurs when the high voltage is faulted at the zero point of the voltage wave. In this case, the first crest of burden voltage occurs one-fourth cycle

Figure 7. Single-phase transient tests for high-capacity 138-kv bushing potential device

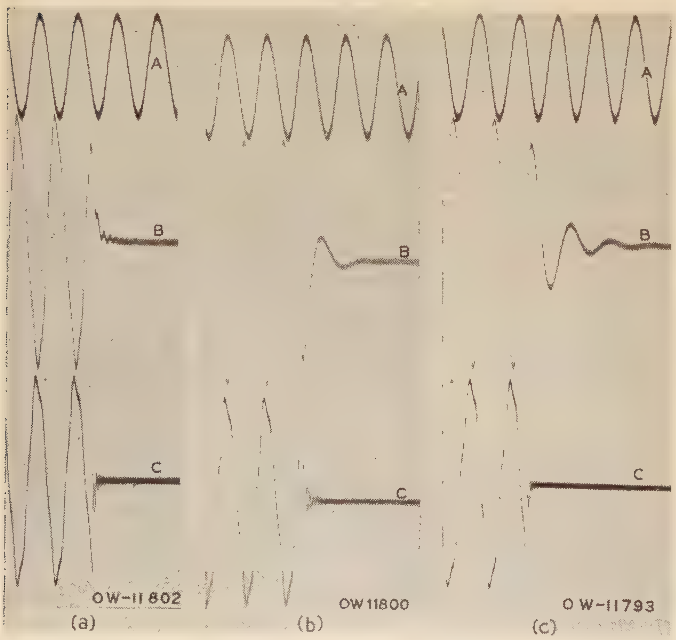
Primary line-to-ground voltage 76.2 kv, 60 cycles; secondary voltage 63.5 volts

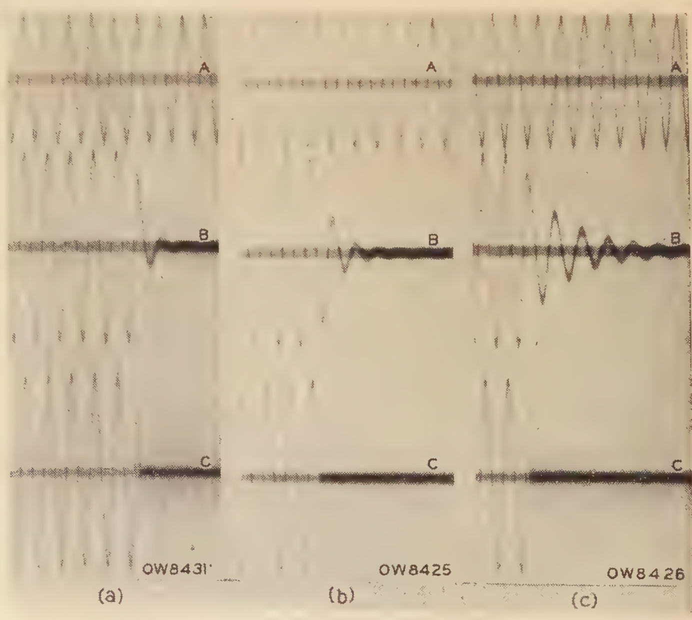
A—Timing wave
B—Secondary voltage
C—Primary voltage

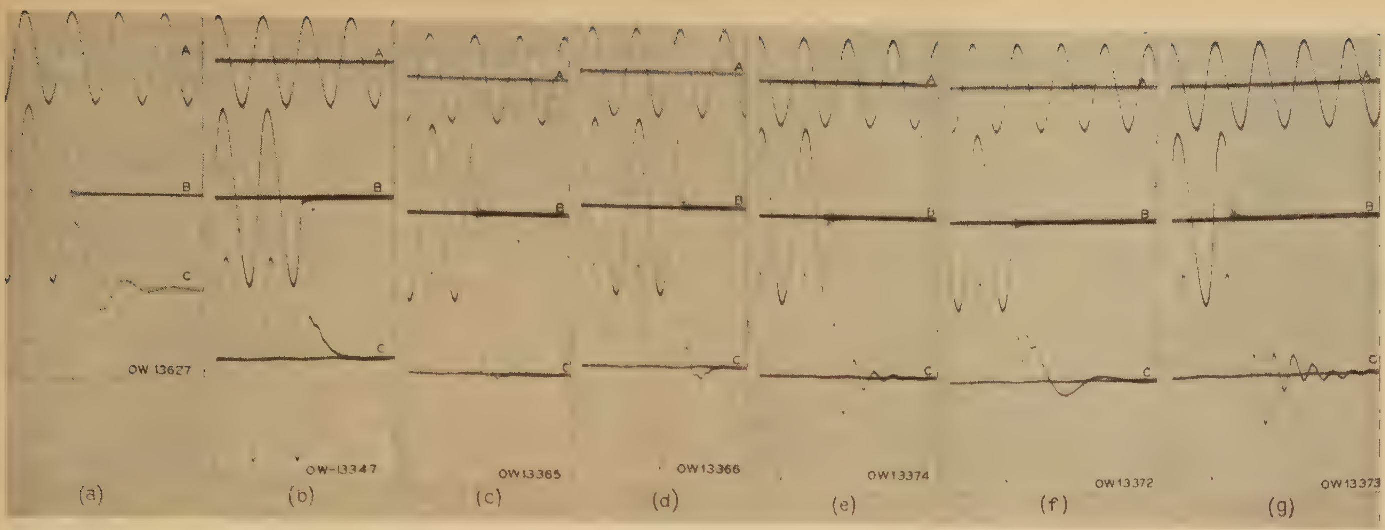
(*a*)—Secondary burden 20 volt-amperes—100 per cent power factor

(*b*)—Secondary burden 40 volt-amperes—100 per cent power factor

(*c*)—Secondary burden 40 volt-amperes—50 per cent power factor lagging







after the primary voltage has been faulted, as shown in figure 5. Its magnitude is the normal value of burden voltage multiplied by the square root of the logarithmic decrement or 34 per cent for the proportions of figure 3*b*. Successive peaks are in the ratio of the logarithmic decrement. Thus the transient performance can be predicted directly from the vector diagram. In this particular case, we find that the transient is oscillatory and has successive peak values of 34 per cent, 3.9 per cent, 0.5 per cent, and so forth, provided the high line voltage is short-circuited at the instant it is passing through zero.

At reduced burdens, the current is decreased and, it is apparent that the reactive voltage drops shown in the vector diagram are smaller in direct proportion. For one-fourth burden, the proportions are 1.1, 0.2, and 0.2 for R, X_L, and X_C respectively. The transient is therefore "dead beat" which emphasizes the important point that the transient can be reduced by lowering the burden on the device.

In a similar manner, the natural frequencies and decrements or time constants have been obtained for the other vector diagrams of figure 3, the results being given in table III. From an analysis of this table, it is evident that a device adjusted for zero phase angle (inductive and capacitive reactances of the device equal) does not guarantee a natural frequency equal to the system frequency, since the burden constants also affect the natural frequency. Furthermore, it is evident that this circuit is not necessarily oscillatory, since a reduction of a resistive burden may increase the ratio of R^2 to $4X_LX_C$ to a point where the transient is "dead beat." Also, it is apparent that a decrease in the source capacitive and inductive reactances improves the transient performance for a given burden.

Figure 8. Single-phase transient tests for standard and modified low-capacity 161-kv capacitor potential device

Primary line-to-ground voltage 80.8 kv, 60 cycles; secondary 67.3 volts

A—Timing wave
B—Primary voltage
C—Secondary voltage

(*a*)—Standard device with secondary burden of 65 volt-amperes—100 per cent power factor

(*b*)—Modified device with secondary burden of 65 volt-amperes—100 per cent power factor and fault at voltage zero

(*c*)—Modified device with secondary burden of 65 volt-amperes—100 per cent power factor and fault at voltage peak

(*d*)—Modified device with secondary burden of 100 volt-amperes—100 per cent power factor

(*e*)—Modified device with secondary burden of 60 volt-amperes—50 per cent power factor leading

(*f*)—Modified device with secondary burden of 60 volt-amperes—50 per cent power factor lagging

(*g*)—Modified device with secondary burden of 60 volt-amperes—50 per cent power factor lagging capacitor corrected to unity power factor

Table II. Correlation of Calculated and Test Transient Data

Figure Number	First Peak in Per Cent of Normal Crest Voltage: Calculated*	Test	Successive Peaks in Per Cent of Previous Peak: Calculated	Test	Natural Frequency (Calculated)
6*b*	51.4		26.5	23.2	60.0
6*c*	70.1		49.3	50.0	60.0
7*a*	52.1		27.3	33.3	60.0
7*b*	73.3	74.0	53.9	50.0	60.0
7*c*	81.9		67.2	65.0	53.8
8*a*	63.0		39.7	41.5	60.0
8*f*	63.8		40.9	35.6	37.4

Based on fault at zero point of voltage wave.

Table III. Natural Frequencies and Decrements Corresponding to Figure 3*

Figure Number	First Peak in Per Cent of Normal Crest Voltage: 100 Per Cent Burden	25 Per Cent Burden	Successive Peaks in Per Cent of Previous Peak: 100 Per Cent Burden	25 Per Cent Burden	Natural Frequency if Oscillatory: 100 Per Cent Burden	25 Per Cent Burden	Time Constants in Seconds†: 100 Per Cent Burden	25 Per Cent Burden
3*a*			45.7	16.4	88.2	117.0	0.00724	0.00193
3*b*	33.8	20.2	11.5	**	60.0	**	0.00386	0.01560
3*c*			49.7	19.2	41.2	26.5	0.00174	0.00115
3*d*			8.4	**	91.0	**	0.00221	0.00807

* Burden composed of resistance and reactance in series. † Long-time constant tabulated for nonoscillatory case. ** Nonoscillatory.

Double-Energy Transients

Two practical cases giving rise to complex circuits are the use of an adjusting capacitor on the transformer secondary

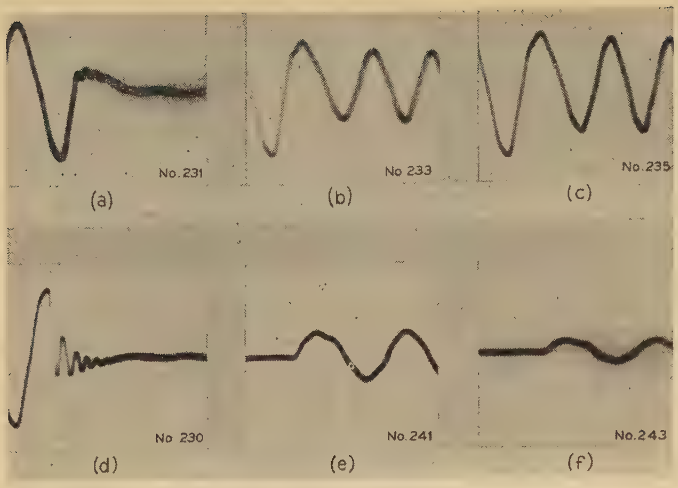


Figure 9. Three-phase transient a-c network calculator tests for modified low-capacity 161-kv capacitor potential device

Primary line-to-ground voltage 80.8 kv, 60 cycles; secondary line-to-ground voltage 67.3 volts. Phase-relay burden 43 volt-amperes—96 per cent power factor lagging; ground-relay burden 29 volt-amperes—75 per cent power factor leading

(*a*)—Phase-relay voltage for fault at device end of line at zero point of voltage wave

(*b*)—Same at middle of line

(*c*)—Same at remote end of line

(*d*)—Same as (*a*) except for fault at peak of voltage wave

(*e*)—Ground-relay voltage for fault at device end of line at zero line point of voltage wave

(*f*)—Same at middle of line

and the use of a capacitor in parallel with the burden for power-factor correction. The first of these in any practical case results in a high-frequency transient of short duration which is unimportant. The latter may produce an undesirable double-frequency transient. In the particular case of correction to unity power factor, the two frequencies are respectively above and below normal system frequency and correspond to the resonance points between the series-connected source impedances and the parallel-connected burden impedances.

Resonance

The terms "resonant", "oscillatory", "nonresonant", and so forth, have been somewhat loosely used in connection with potential devices in the past. In view of the foregoing discussion, they should be analyzed in an effort to define their meaning as applied to these devices and, if possible, to adopt more appropriate nomenclature for the various devices available.

The term "nonresonant" applies strictly to steady-state conditions. It is, however, ambiguous and has in some cases been confused as implying a freedom from the effects of oscillation of the burden voltage when changing to a new level. Nonresonant devices are actually a simpler, cheaper form of device, termed "nonresonant" because they do not have the equal capacitive and inductive reactive branches in the source. Actually, this simply means that such a device does not resonate at system frequency with a pure resistance burden. It will, of course, resonate at some other frequency if the burden includes inductance, as it usually does, and will involve the double-energy transients mentioned above if corrective capacity is used with the burden. The term "nonresonant" has also been used to distinguish such a device from the resonant device which has good regulation. Since the standard potential devices (so called "resonant" devices) may have superior performance characteristics under both steady-state and transient conditions, it would be preferable to distinguish them from the less elaborate arrangement by referring to the latter as the "simplified" device, which would not involve any implication as to its relative transient performance.

Transient Test Data

A comprehensive series of transient tests were made to verify the theory outlined above, as well as to show the transient characteristics which may affect the performance of high speed relays, and the efficacy of several means of control. These investigations included field tests previously described,[2,3] single-phase fault tests made on typical devices in the factory, and a-c network-calculator tests.

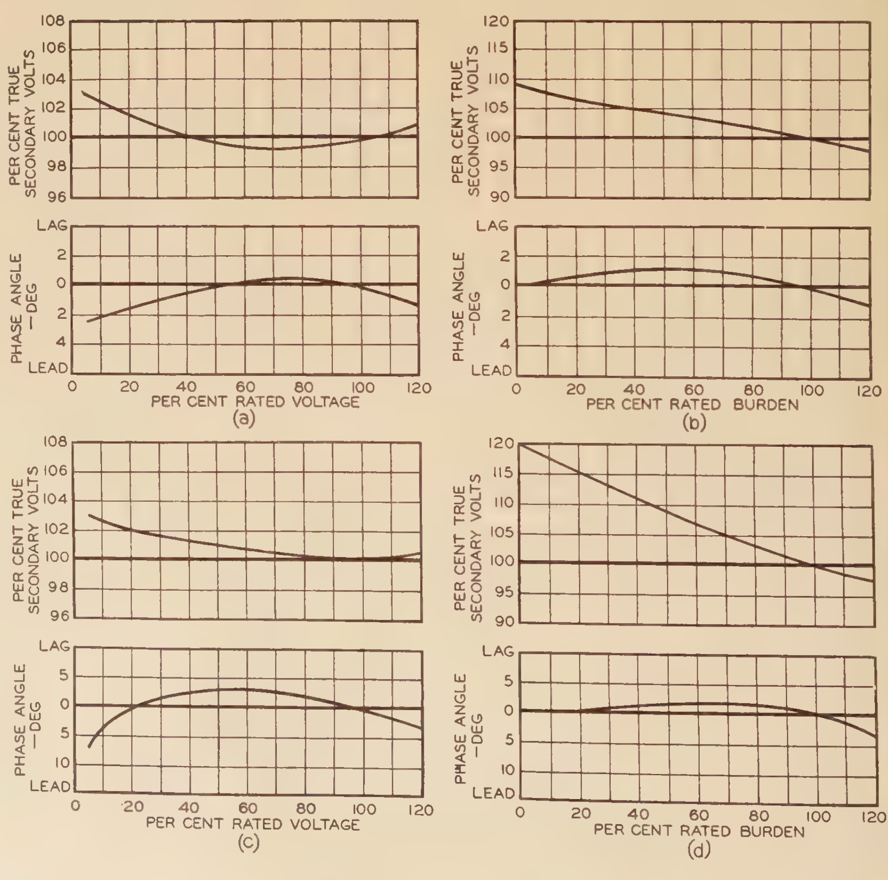
Figure 10. Capacitor and bushing potential-device performance curves

(*a*)—High-capacity 161-kv 60-cycle capacitor potential device—voltage performance

(*b*)—High-capacity 161-kv 60-cycle capacitor potential device—burden performance

(*c*)—High-capacity 161-kv 60-cycle bushing potential device—voltage performance

(*d*)—High-capacity 161-kv 60-cycle bushing potential device—burden performance



In the latter the recently devised method[4] for utilizing the a-c network calculator for transient studies was employed. While 115 and 66.5 volts are the standard line-to-line and line-to-neutral voltages, respectively, the test data have been taken at the various service voltages indicated in the captions.

Figure 11. Low-capacity 115-kv capacitor potential device equipped for carrier-current coupling

Figures 6, 7, and 8 illustrate typical single-phase tests, and in general show natural frequencies, amplitudes, and decrements of the burden voltage transient as expected from the theoretical analysis, this correlation being indicated in table II. Since the point of voltage wave at which fault occurs was not controlled in these tests, the magnitude of the first peak after the fault could be compared only in the one case where the fault occurred at the zero point of the voltage wave. Of particular interest are the effects of burden variations figures 7*b* and *c*, and figures 8*c*, *e*, *f*, and *g*. Figures 8*a* and *b* illustrate the improvement obtained by modifying the device as suggested by the theory. Figure 8*g* shows the double-energy transient resulting from power-factor correction of the burden by parallel capacitor. The "subtransient" resulting from the use of adjusting capacitors on the secondary of the transformer is evident in several of the oscillograms of figure 8. Comparison of figures 8*b* and *c* illustrates that the maximum overshoot is obtained for a fault at the zero point of the voltage wave.

The a-c network calculator has been shown to give natural frequencies, amplitudes, and decrements of the transient in close agreement with theoretical methods and with results obtained by oscillographic tests on actual devices. Its flexibility has made possible a thorough analysis covering a wide range of conditions. This study has included for example the effect of location of fault along the transmission line, the effect of point on the voltage wave at which a fault occurs, and of different types of faults such as three phase, line-to-line, line-to-ground, and double line-to-ground. The effects of various proportions and arrangements of the device parts have been studied, a modified device having resulted from this study. The transients have been observed on the ground relays and on the phase relays of sound and faulted phases with balanced and unbalanced arrangements of relay burdens.

Typical photographic records of these tests are given in figure 9, parts *a*, *b*, and *c* illustrate the effect of moving the fault along the transmission line, *a* and *d* the effect of point on the voltage wave at which the fault occurs, and *e* and *f* show the ground relay voltage for faults at the zero and peak points of the voltage wave. The subtransient is maximum for faults at the peak of the wave where a quick energy dissipation in the capacitance divider is necessary. The main transient is greatest for fault at the zero point of the wave.

Conclusions

A general method has been presented utilizing an equivalent circuit for analyzing the performance of potential devices from a design and application standpoint, a method which offers an advantageous point of view for visualizing the phenomena involved as well as providing the specific solutions. This method, including the use of symmetrical components for unbalanced system conditions, covers both steady-state and transient performance. The a-c network-calculator method of transient testing has been found to give reliable engineering results in this problem even though both the power system and measuring system constants needed to be represented simultaneously on the calculator circuits.

Improvements in transient performance have been found possible by changes in design constants, and tests on devices built in line with the theory have shown the expected improvements. It has been shown that the transient phenomena is roughly divisible into a subtransient due to adjusting capacity on the secondary of the transformer, and a main transient in the series circuit composed of the device and its burden. The subtransient is negligible due to its short duration and high frequency. The main transient is of considerable importance, and proper control should be exercised in design and loading to keep it within application requirements. Low noninductive burdens result in the best performance. Double-energy main transients may be avoided by omission of burden-paralleling capacitors.

The studies described have afforded basis for the design of a new capacitor potential device utilizing a variable reactance transformer and having windings for supplying simultaneously star- and delta-connected phase burdens and residual burdens.

Appendix I. Steady-State Performance

Nomenclature

Fundamental Constants

On circuit voltage base, refer to figure 2 except as noted.

Z_a —Impedance of stack capacity
Z_c —Impedance of tap capacity
Z_x —Transformer exciting impedance, primary basis
Z_t —Transformer leakage impedance, primary basis
n —Transformer turns ratio, high voltage to low voltage
Z_s —Impedance of tuning capacity, in parallel with tap capacity but located on secondary side of transformer
Z_r —Impedance of the variable reactor
Z_b —Burden impedance
Z —Source impedance to burden, secondary basis
E_h —High line voltage to ground
E_c —Tap voltage to ground
E_b —Burden voltage
E_{b0}—Burden no-load voltage
A —Over-all potentiometer effect multiplier
k —Over-all no-load transformation ratio E_h/E_{b0}

$$\frac{1}{k}=\frac{A}{n}$$

Other derived and intermediate quantities are defined by the equations.

Derivation of Equivalent Circuit, Figure 2 (dotted capacitor not used)

In figure 2*b* the parallel of Z_c and Z_x is

$$Z_{cx}=\frac{Z_cZ_x}{Z_c+Z_x} \qquad (1)$$

By Thevenin's theorem the potentiometer circuit composed of Z_a and Z_{cx} may be replaced by the simple series circuits of figure 2c in which:

$$nE_{bo}=\frac{Z_{cx}}{Z_a+Z_{cx}}E_h=AE_h \tag{2}$$

where E_{bo} is seen to be the burden no-load voltage.

$$A=\frac{Z_{cx}}{Z_a+Z_{cx}} \tag{2a}$$

$$Z_{acx}=\frac{Z_{cx}}{Z_a+Z_{cx}}Z_a \tag{3}$$

and being essentially capacitive reactance is shown as such. The transformer leakage impedance and the reactor combine to form the inductive reactance of the source,

$$n^2Z_{tr}=Z_t+n^2Z_r \tag{4}$$

In figure 2d the secondary turns base has been used although this is purely a matter of preference. The total source impedance on this base is:

$$Z=\frac{Z_{acx}}{n^2}+Z_{tr} \tag{5}$$

The "burden performance" of the device, or ratio and phase-angle regulation, may be expressed in the form:

$$E_b=E_{bo}-I_bZ \tag{6}$$

$$E_b=\frac{A}{n}E_h-I_bZ \tag{6a}$$

where the no-load voltage E_{bo} and the source impedance Z are defined above.

Derivation of Equivalent Circuit, Figure 2 (dotted capacitor used)

The capacitance divider and transformer exciting impedance can be converted as before to an equivalent series circuit having internal voltage E_z and impedance Z_{acx} defined as follows.

$$Z_{cx}=\frac{Z_cZ_x}{Z_c+Z_x} \tag{7}$$

$$E_z=\frac{Z_{cx}}{Z_a+Z_{cx}}E_h \tag{8}$$

$$Z_{acx}=\frac{Z_{cx}}{Z_a+Z_{cx}}Z_a \tag{9}$$

Combining the source with the transformer leakage impedance, the new source impedance Z_{acxt} is defined, the internal voltage being still given by (8)

$$Z_{acxt}=Z_{acx}+Z_t \tag{10}$$

On the primary turns base the adjusting capacitor has an impedance n^2Z_s. Converting the potentiometer circuit formed by Z_{acxt} and n^2Z_s by a series circuit, according to Thevenin's theorem, an internal voltage nE_{bo} and impedance Z_{acxts} are obtained.

$$nE_{bo}=\frac{n^2Z_s}{n^2Z_s+Z_{acxt}}E_z$$

$$=\frac{n^2Z_s}{n^2Z_s+Z_{acxt}}\cdot\frac{Z_{cx}}{Z_a+Z_{cx}}E_n \tag{11}$$

or

$$nE_{bo}=AE_h \tag{12}$$

where

$$A=\frac{n^2Z_s}{n^2Z_s+Z_{acxt}}\cdot\frac{Z_{cx}}{Z_a+Z_{cx}} \tag{13}$$

Also

$$Z_{acxts}=\frac{n^2Z_s}{n^2Z_s+Z_{acxt}}Z_{acxt} \tag{14}$$

This term is essentially capacitive in cases where the adjusting capacity is used at all, and corresponds roughly to z_{acx} of figure 2d. Combining it in series with the reactor, the over-all source impedance Z becomes on the secondary turns base:

$$Z=\frac{Z_{acxts}}{n^2}+Z_r \tag{15}$$

and the burden performance characteristic is:

$$E_b=E_{bo}-I_bZ \tag{16}$$

or

$$E_b=\frac{A}{n}E_h-I_bZ \tag{16a}$$

where A and Z are defined by equations 13 and 15.

Appendix II. Symmetrical-Component Resolution

(Refer Also to Appendix I)

Nomenclature

E —Voltage
a, b, c —Phases
1, 2, 0 —Sequences
h —High-voltage line
p, u, v, w—Turns or turns base designation

Examples: E_{u2}, negative-sequence voltage, line-to-neutral at location indicated in figure 4 on turns base u; E_{h1}, positive-sequence component of the set E_{ha}, E_{hb}, E_{hc}.

In figure 4 the derivation of sequence networks on the particular turns base u follows well-known theory. The ratio n used in determining Z and the applied voltage should include not only the main transformer, but also the auxiliary transformer from p to u. The auxiliary transformer when liberally designed may be treated as a "perfect" transformer of negligible exciting and leakage impedances or if not negligible it may be treated as a three-winding transformer since not more than three windings are involved in any sequence network. The zero-sequence impedance on turns base u due to the load Z_{bw} is in general $\frac{Z_{bw}}{3}\left(\frac{u}{w}\right)^2$ which for the particular ratio shown is $Z_{bw}/9$.

The corresponding general expression for E_{bw} is

$$E_{bw}=3\frac{w}{u}E_{u0} \tag{17}$$

Under both normal and fault conditions the voltage E_{ha}, E_{hb}, E_{hc}, and hence the voltages E_{h1}, E_{h2}, E_{h0}, will be fixed rigidly by the power-system constants and the type and location of fault.

The corresponding burden sequence voltages are determined from the sequence networks, figure 4c.

$$E_{u1}=\frac{Z_{b1}}{Z+Z_{b1}}\frac{A}{n}E_{h1} \tag{18}$$

$$E_{u2}=\frac{Z_{b2}}{Z+Z_{b2}}\frac{A}{n}E_{h2}=\frac{Z_{b1}}{Z+Z_{b1}}\frac{A}{n}E_{h2} \tag{19}$$

$$E_{u0}=\frac{Z_{b0}}{Z+Z_{b0}}\frac{A}{n}E_{h0} \tag{20}$$

From these the burden line-to-neutral voltages are obtained

$$E_{ua}=\frac{A}{n}\left[(E_{h1}+E_{h2})\frac{Z_{b1}}{Z+Z_{b1}}+E_{h0}\frac{Z_{b0}}{Z+Z_{b0}}\right] \tag{21}$$

$$E_{ub}=\frac{A}{n}\left[(a^2E_{h1}+aE_{h2})\frac{Z_{b1}}{Z+Z_{b1}}+E_{h0}\frac{Z_{b0}}{Z+Z_{b0}}\right] \tag{22}$$

$$E_{uc}=\frac{A}{n}\left[(aE_{h1}+a^2E_{h2})\frac{Z_{b1}}{Z+Z_{b1}}+E_{h0}\frac{Z_{b0}}{Z+Z_{b0}}\right] \tag{23}$$

Adding and subtracting a zero-sequence term:

$$E_{ua}=\frac{A}{n}(E_{h1}+E_{h2}+E_{h0})\frac{Z_{b1}}{Z+Z_{b1}}-E_{h0}\frac{Z_{b1}}{Z+Z_{b1}}+E_{h0}\frac{Z_{b0}}{Z+Z_{b0}}$$

$$=\frac{A}{n}\frac{Z_{b1}}{Z+Z_{b1}}E_{ha}+E_{h0}\frac{A}{n}\left[\frac{Z_{b0}}{Z+Z_{b0}}-\frac{Z_{b1}}{Z+Z_{b1}}\right] \tag{24}$$

Similarly

$$E_{ub}=\frac{A}{n}\frac{Z_{b1}}{Z+Z_{b1}}E_{hb}+E_{h0}\frac{A}{n}\left[\frac{Z_{b0}}{Z+Z_{b0}}-\frac{Z_{b1}}{Z+Z_{b1}}\right] \tag{25}$$

$$E_{uc}=\frac{A}{n}\frac{Z_{b1}}{Z+Z_{b1}}E_{hc}+E_{h0}\frac{A}{n}\left[\frac{Z_{b0}}{Z+Z_{b0}}-\frac{Z_{b1}}{Z+Z_{b1}}\right] \tag{26}$$

Equations 24, 25, and 26 show that with zero-sequence voltage present, and zero- and positive-sequence burdens unequal, the ratio of high to burden line-to-neutral voltages is not a constant, but depends on the zero-sequence voltage, the difference in burdens (Z_{b0} and Z_{b1}) and the stiffness of the device (value of Z). If Z is small, both terms in the parenthesis approach one resulting in a relatively small voltage error. Also if the positive- and zero-sequence burdens are made equal the voltage error can be eliminated.

The delta voltages may be obtained by subtracting equations 24, 25, and 26 in pairs and defining the high line-to-line voltage as

$$E_{hab}=E_{ha}-E_{hb} \tag{27}$$

$$E_{uab}=E_{ua}-E_{ub}=\frac{A}{n}\frac{Z_{b1}}{Z+Z_{b1}}E_{hab} \tag{28}$$

$$E_{ubc}=\frac{A}{n}\frac{Z_{b1}}{Z+Z_{b1}}E_{hbc} \tag{29}$$

$$E_{uca}=\frac{A}{n}\frac{Z_{b1}}{Z+Z_{b1}}E_{hca} \qquad (30)$$

Equations 28 to 30 show that the ratio of high to burden delta voltages is a constant independent of the residual burden, the system constants, and type of fault.

The residual voltage is

$$E_{bw}=3\frac{w}{u}E_{u0} \qquad (31)$$

and from equation 20

$$E_{bw}=3\frac{w}{u}\frac{Z_{b0}}{Z+Z_{b0}}\frac{A}{n}E_{h0} \qquad (32)$$

Equation 32 shows that the ratio of high zero-sequence voltage to residual voltage is a constant independent of the amount of delta burden, the system constants, and the type of fault.

Appendix III. Transients

The equivalent circuit, figure 2*d*, with the slight approximation of ignoring Z_z, is also an equivalent under transient conditions. It shows that the device and its connected burden may be treated as a series circuit of R, L, and C, provided the burden approximates a resistance or resistance and reactance in series. Tests indicate that this is generally the case unless burden-power-factor-correction capacitors are used.

It is well known that the R, L, C series circuit is oscillatory only if

R^2 is less than $\frac{4L}{C}$

or if

R^2 is less than $4X_LX_C$

where X_L and X_C are the inductive and capacitive reactances at any arbitrary frequency such as 60 cycles. If R^2 is greater than given by this value, the circuit is not oscillatory but "dead beat."

Nonoscillatory Case

R^2 is greater than $4L/C$.

The solution for current i, as a function of time t, for pure resistance burden with fault occurring at the instant of current zero (which coincides with burden voltage zero) is a unidirectional surge as follows.

Burden Current

$$i=A(\epsilon^{\frac{-t}{T_1}}-\epsilon^{\frac{-t}{T_2}}) \qquad (33)$$

where

$$A=\frac{\sqrt{2}E_0}{L}\cdot\frac{T_1T_2}{T_1-T_2} \qquad (34)$$

in which E_0 is the root-mean-square capacitor voltage prior to the fault.

Time Constants

$$T_1=\frac{2L}{R-\sqrt{R^2-\frac{4L}{C}}}\text{ seconds} \qquad (35)$$

$$T_2=\frac{2L}{R+\sqrt{R^2-\frac{4L}{C}}}\text{ seconds} \qquad (36)$$

T_1 is the long-time constant determined largely by RC, and fixes the decay of the surge. T_2 is the short-time constant determined largely by L/R and determines the shape of the front of the wave. The exact values are given by equations 35 and 36.

The burden voltage following the fault is:

Burden Voltage

$$e_b=iR_b=R_bA(\epsilon^{\frac{-t}{T_1}}-\epsilon^{\frac{-t}{T_2}}) \qquad (37)$$

This is a unidirectional surge of voltage which reaches its crest in a time:

Time to Crest

$$t_m=\frac{T_1T_2}{T_1-T_2}\log\frac{T_1}{T_2} \qquad (38)$$

Crest Value

$$e_b\max=R_bA(\epsilon^{\frac{-t_m}{T_1}}-\epsilon^{\frac{-t_m}{T_2}}) \qquad (39)$$

Oscillatory Case

R^2 less than $4L/C$.

The solution for fault occurring at the zero point of the voltage wave with pure resistance burden is an oscillation of the form

$$e_b=e_{b0}\epsilon^{\frac{-t}{T}}\sin 2\pi f_0t \qquad (40)$$

where e_{b0} is the crest value of steady-state voltage prior to the fault.

The characteristic factors are given as follows:

Natural Frequency

$$f_0=\frac{1}{4\pi L}\sqrt{\frac{4L}{C}-R^2}\text{ cycles per second} \qquad (41)$$

Time Constant

$$T=\frac{2L}{R}\text{ seconds} \qquad (42)$$

Ratio of Successive Peaks or Decrement (Refer to figure 5)

$$D=\frac{e_{b2}}{e_{b1}}=\epsilon^{\frac{-1}{2Tf_0}}=\epsilon^{\frac{-R}{4Lf_0}}=\epsilon^{\frac{-\pi R}{2X_{L0}}} \qquad (43)$$

where the inductive reactance at natural frequency is X_{L0}.

Successive peaks are one-half cycle apart whereas the initial peak occurs but one-fourth cycle after the fault. The first peak is:

First Peak

$$\frac{e_{b1}}{e_{b0}}=\sqrt{D} \qquad (44)$$

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Discussion

H. A. P. Langstaff (West Penn Power Company, Pittsburgh, Pa.): The West Penn Power Company has made extensive use on the 132-kv transmission system of the bushing-type potential device closely allied in characteristic operation with the pedestal or suspension-type capacitor potential device, none of which have been used. Thirty-six bushing potential devices are now in active service located at seven 132-kv substations. The evident economy in cost of apparatus and in simplification of structure layout has well warranted the selection and use of this equipment. Purchase and installation has extended from 1927 to the present year; the two original devices purchased in 1927, rebuilt and modernized, are still in service.

The uses to which the devices have been put are as follows:

1. To obtain potential indication and source of synchronizing potential for incoming 132-kv lines. In two instances synchronism is checked from a device on one line to a device on another line. In other instances it is from a line device to a standard potential transformer. Where a phase difference occurs such as in synchronizing from the phase-to-ground-connected device to a phase-to-phase-connected potential transformer it has been compensated for by adjusting the phase angle of the potential device, a very convenient and wholly satisfactory method.

2. To obtain potential for directional phase relays and with the use of an auxiliary star-series potential transformer for directional ground relays.

3. To obtain zero-sequence potential for directional ground relays. In this instance a three-phase potential unit was constructed composed of two open-delta-connected standard 132-kv potential transformers, to the three external 132-kv bushings of which were attached three bushing potential devices. The potential transformers are used for directional phase relays and the bushing potential devices supply zero-sequence voltage for directional ground relays. Two of these complete three-phase units are installed at Charleroi substation, one on each section of the 132-kv bus. To each unit is connected the phase and ground protective relays of four incoming 132-kv lines. These units, designed by West Penn Power Company and assembled by the Westinghouse Electric and Manufacturing Company constituted an economical and satisfactory means of obtaining the desired result using potential transformer cores available for that purpose. The tanks are large enough to take a third potential transformer core.

4. At the Kiski Valley substation three devices on a 132-kv breaker are connected to detect zero-sequence potential and to cause the breaker to trip, if a 132-kv ground fault persists for a period exceeding the time setting of a voltage relay. (The 132-kv bank winding is delta connected at this substation.)

The first potential device was put in service on May 10, 1928, and was used for 132-kv line potential indication and for synchronizing. An article by the writer in the *Electrical World* of November 24, 1928, described this application. On April 6, 1938, a series of 132-kv ground-fault tests was made on a complete directional phase and ground relay application at Washington substation where two incoming 132-kv lines connected to a bus from which power was distributed through two 15,000-kva banks. One bushing on the line side of each

line breaker was equipped with a potential device for line potential indication and for synchronizing. Three devices on the bus side bushings of each breaker supply potential to phase and ground protective relays. Oscillograph records were taken by the Westinghouse company and the analysis proved the acceptability of the potential devices for protective work.

Troubles and poor performance which were experienced on the devices purchased during their early stage of development were due almost wholly to causes originating in the lead-in cables. Corona deterioration occurred in the cables and breakdown occurred in the bayonet due to moisture entering through poorly made joints. About 20 cables were replaced in 1931 and some of them have given trouble since that time from the same causes. Due to this experience bayonet and cable improvements have been made and the present connected bayonet and cable gives promise of being free from the past troubles.

A special star-series auxiliary potential was designed for West Penn Power Company use in order that zero-sequence potential might be obtained and it has been used with complete success with the potential devices. In figure 4*a* of the paper under discussion is shown an auxiliary transformer, apparently now an integral part of the potential device, which makes available without any external apparatus voltage for line-to-neutral burden, line-to-ground burden, and residual burden. The Westinghouse company is to be congratulated upon this improvement.

The performance on the West Penn Power Company 132-kv system of the potential devices has been entirely satisfactory so far as electrical characteristics are concerned. They have not been called upon to operate with relays of the impedance type or of modern high-speed nature. Hence many of the problems and their solution discussed in this paper by Messrs. Harder, Langguth, and Woods have not been encountered, sufficient time of relay operation having obviated the effect of transient variations.

J. D. Laughlin and **T. M. Blakeslee** (Bureau of Power and Light, City of Los Angeles, Calif.): From an operating standpoint, it is gratifying to read a paper demonstrating such complete concordance of performance with theory as is disclosed in the paper by Messrs. Harder, Langguth, and Woods.

The protection of important transmission lines with high-speed relays has developed to a point where it is highly desirable, if not absolutely necessary, that potential sources, as well as current sources, for the relays be obtained from devices inside the protected circuit.

Instrument potential with sufficient accuracy for relaying purposes can be obtained from capacitor potential devices and the capacitors can also be used as coupling devices for carrier-frequency circuits. The dual functions of these devices and their lower cost justifies their use in many installations that might be questioned if standard potential transformers had to be used.

Since the most important use of these devices is for obtaining relay potential, and as relays function only under fault conditions on a system, it seems highly important that these devices be designed to reproduce accurately the primary voltage conditions when the system voltage is low and to remain stable when surges appear on the line.

As explained in the paper, there are many variations of the device circuit, some of which are not adaptable to all applications. The oscillograms in the paper show that for some secondary circuits with resonant characteristics the secondary voltage may continue for a time after the interruption of the primary voltage. This condition is undesirable for applications using relays with potential restraint coils that are expected to function in less than one cycle. The accurate predetermination of performance is necessary to select the proper type of device for specific applications.

The development of potential devices with multiple secondary voltages for obtaining delta, star, and residual voltages has simplified relay installations.

Prior to the application of potential devices on the Boulder transmission lines, instability, due to the parallel circuit made up by the auxiliary or tap capacity and the device transformer, was discovered in certain capacitor potential devices by our testing laboratories. This was corrected, however, before extensive use of the units, with the result that their performance in service has been satisfactory. This unstable phenomenon is that referred to by Mr. Clem (reference 6) and was corrected by designing the device transformer with low magnetic density so that the circuits approach the linearity assumed in the mathematical analysis presented in the paper under discussion.

The Los Angeles Bureau of Power and Light has accepted the increasing popularity of capacitor potential devices. All 287,500-volt lines are completely equipped to provide potential for relays, meters, indicating lamps, and for synchronizing. The capacitors are also used to couple carrier-frequency circuits to the lines, there being three carrier-frequency circuits operating over each transmission circuit. The bulk of the 110-kv and 132-kv lines are also fully equipped, and there are some installations on 34.5-kv lines.

Since the potential device bids fair to take the place of the more expensive potential transformer in every application, except that of power metering, some standardization of nomenclature would be desirable. The present paper points out the ambiguity of the terms "resonant" and "nonresonant." The capacity, which is in series with the line, is identified by the authors of this paper as the "stack capacity," whereas other authors refer to this as the "coupling capacity." The capacitor in parallel with the potential device is called the "tap" and "auxiliary" capacity, respectively, by different authorities.

The ability of the manufacturer to predict accurately the performance of these devices, as disclosed in this paper, will be of great assistance to application engineers by permitting them to take full advantage of their uses, select the proper type of devices for individual applications, and use them with confidence.

L. F. Kennedy (General Electric Company, Schenectady, N. Y.): Successful relay application requires complete knowledge of the characteristics of the sources of supplies of current and potential. This paper dealing, as it does, with a frequently used source of potential is of interest to all relay engineers. The fact that it recognizes the importance of the transient as well as the steady-state conditions of potential devices should make it of increased value.

The requirements for a supply of relay potential may be very briefly summarized as follows: For directional relays the phase-angle error should be small and reasonably constant; for distance relays or other relays using voltage restraint the ratio error should be small. Both types of relays of modern construction are precision instruments carefully designed to operate correctly under certain assumed conditions.

Let us consider for a moment what has been shown in the paper by Mr. Harder and his associates. Figure 8*a* shows that several half cycles of apparently normal frequency are required for one standard potential device secondary voltage to reach zero after the primary voltage has been made zero. Other illustrations show various transients of which some are negligible and others persist for several oscillations. These latter show frequencies which vary from half normal to more than twice normal.

The first type of transient, that in which there is no change in frequency, but only a time delay before reaching a new level, will in general have only the effect of slowing up the relay response. The second type, that in which there is a change in frequency, must be separately considered for different types of relay elements. As already indicated, the relays are designed for precision operation under certain assumed conditions, one of which is that energy is supplied at rated frequency. It is, of course, obvious to all of us that a modern high-speed directional relay energized with current at normal frequency but with a voltage of half normal frequency as shown in figure 8*f* would respond erratically and oscillate each half cycle instead of producing its expected steady torque in one direction.

Other types of relays will, of course, respond differently and each kind must be separately investigated. Some relays have circuits which are carefully tuned for normal frequency and these cannot help but be affected by changes in frequency.

The ideal potential supply, therefore, would seem to have as its first requirement a low and fixed phase-angle error under transient as well as steady-state conditions; thus any frequency shift is prevented. As a second requirement, of course, would be a low and fixed ratio error but if there was a transient error which resulted in a secondary voltage which at times was higher than expected (as in figure 8*a*), this could be used except in rare cases where the slight increase in over-all time of relay operation was of the utmost importance.

The authors have concluded that a low burden which is noninductive will give the best results and that burden-paralleling capacitors should be avoided. All relay potential coil circuits are inductive and to obtain the noninductive load, it is necessary either to especially design the relay elements with series capacitors to obtain the noninductive circuit for potential device applications only, or if a standard relay applicable to other sources besides the po-

tential device is used, then the noninductive characteristics of the load can only be obtained by the use of paralleling capacitors. We should not overlook the fact, at this part of the discussion, that many relays, which have what appears a noninductive burden, obtain this through the use of internally mounted capacitors. This paper, while pointing out in its theoretical considerations how to obtain the desired results, fails to complete the job by insertion of tabular data which the average application man could use to determine whether or not his particular case would have trouble from transients.

I was rather surprised to note in appendix III that the equivalent circuit under transient conditions was set up by making the approximation of omitting Z_x. Since Z_x represents the magnetizing or exciting component, it is somewhat surprising to find this element ignored in any transient study. It may be that the potential device is greatly different from all other circuits containing an iron-core element, but past experience certainly indicates that the variations in the value of Z_x under various transient conditions would play a very large part in determining the over-all device performance. I will be glad to have the authors' comments on what recorded data they have which justifies this assumption.

Ralph Higgins (The Ohio Brass Company, Barberton, Ohio): Secondary transients have long been recognized as one of the inherent characteristics of capacitance potential devices and the authors additional contribution to this problem is indeed a worthy effort and quite instructive. To reduce the transient effect, the authors of this paper have shown that the best results can be expected when the burden requirements, both the resistive and the inductive components, are reduced to a minimum. While this is quite true, an impression is apt to be conveyed that one must limit the burden requirements when desiring to operate high-speed relays from capacitance potential devices. Thus, it would seem that the economies effected by the use of this potential device would be questionable if one must limit the available output from this type of equipment which already has a limited output. Also, it is noted that the authors have stressed the effect of the burden-paralleling capacitance generally used to adjust the phase-angle relation and to correct the power factor of the burden.

Figure 1 of this discussion shows a simple modification of the usual capacitance-potential-device circuit which may be employed very effectively to dampen out any undesired transient oscillations, and at the same time, this scheme requires only a slight reduction in the available output. Quite a few successful installations have been made of this scheme within the last few years.

This damping effect is accomplished by means of two adjusting resistors, one in parallel with the burden, the other in parallel with the transformer secondary. The usual adjusting capacitor, instead of being connected directly in parallel with the burden, as is the usual practice, is connected from one side of the burden to a higher tap on the transformer secondary. Hence any oscillatory circuit that may be set up in series with this capacitance will also be in series with the transformer winding; and thereby can be made nonoscillatory or deadbeat by means of the resistor paralleling this winding.

Figure 2 shows a few typical oscillograms taken during a three-phase laboratory setup, using 138-kv bushing potential devices energized to full potential, to simulate double line-to-ground faults close to the station. This type of fault, perhaps, presents the most hazardous condition resulting from transients upon the operation of high-speed directional line relays.

Oscillogram *A*, taken of the voltage across the relay on the short-circuited secondary phase, illustrates the effectiveness of the damping accomplished with the potential devices loaded to the full rated output, and with a highly inductive burden. While the transient as shown by this oscillogram is not completely damped within the first cycle, and therefore the transient performance may not be ideal, nevertheless, repeated tests show that successful relay operation could be expected from the arrangement.

Oscillogram *B* illustrates the improvement accomplished by reducing only the inductive component of the burden, and oscillogram *C* that accomplished by a further reduction of both the resistive and inductive components.

We are in full agreement with the authors' objection to the classification of various types of potential devices as either resonant or nonresonant. The term "resonant" is usually associated with a circuit requiring accurate tuning. To obtain the desired adjustment with the network, as shown in figure 1, the potential device can be given an in-phase adjustment, and yet no part of the network need be in resonance at the normal operating line frequency. Also, with the same set of adjusting impedances required for an in-phase adjustment, it is possible to obtain practically any other desired phase-angle relation from 30 degrees lagging to 120 degrees leading with very little change in the available output. Figure 3 is a schematic diagram of such an arrangement. The adjustments requiring a large lead angle are accomplished by simply connecting the adjusting reactor in parallel with the burden. Since the one type of potential device may be made applicable to all normal requirements, it naturally may not come under the nomenclature of resonant or nonresonant.

Another important advantage gained by the use of this network scheme is that numerous tap connections on the transformer are not necessary to meet the normal adjustment requirements of the potential

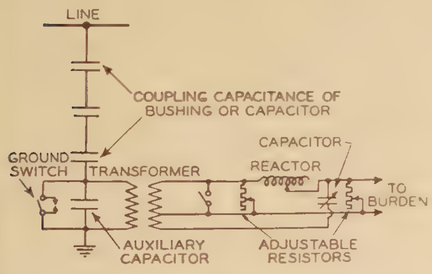

Figure 1

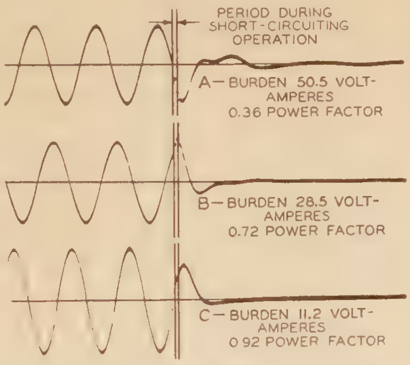

Figure 2

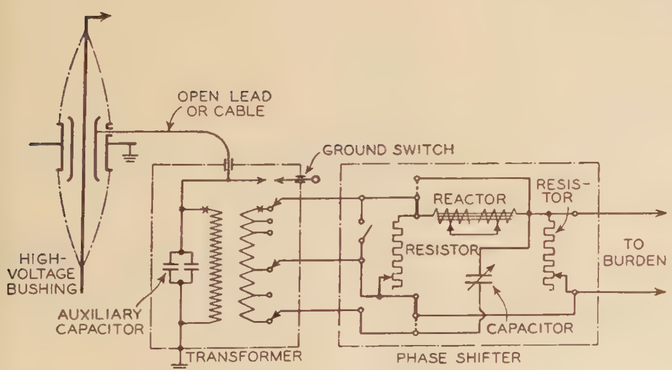

Figure 3

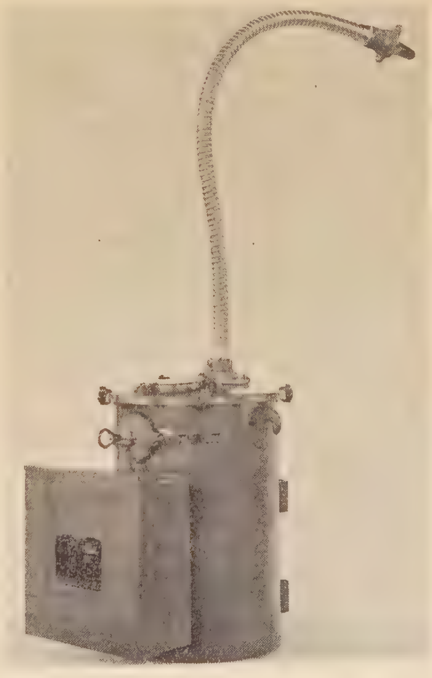
Figure 4

device. This feature readily permits the mounting of the various adjusting impedances in a small cabinet separate from the transformer housing. Figure 4 shows the improved standard potential device used in connection with capacitance tap bushings. Since only three leads are used between the transformer and the adjusting network, it is sometimes found convenient to mount this cabinet in the station close to the burden.

C. A. Powel (Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): The potential devices referred to in this paper are those used in connection with transformer or circuit-breaker bushings or with coupling capacitors to obtain potential from high-voltage circuits without the use of the more usual but more expensive potential transformer. The Westinghouse company first devised these capacitance transformers back in 1928 by the simple process of tapping the outside layers of their well-known condenser bushings. The low-voltage tapped section of the capacitor supplies a network device consisting of a small transformer, adjustable reactors and capacitors variously connected, depending on what it is to be used for.

With the advent of high-speed relaying, it was found that the potential devices built for other purposes did not give entirely satisfactory results with such relays, which operate in from one to three cycles. When the line potential fell, the secondary voltage in these devices was found not to follow immediately, and, moreover, it might oscillate about the new level for several cycles. If it happened that the line potential went to zero, the secondary voltage might even overshoot so that the relay obtained an indication of voltage in the wrong direction.

In the course of solving this difficulty, the authors developed an analytical method of investigating what happens in the devices under transient as well as steady-state conditions. To date, such a tool has not been available. The analytical method can readily be carried out for a simple single-phase circuit, but when the circuit becomes involved by virtue of unbalanced faults, the analytical work becomes very burdensome if not almost impossible.

The authors, therefore, for such cases, have adopted the method developed by R. D. Evans and A. C. Monteith described in AIEE TRANSACTIONS, volume 56, 1937, pages 695–703, of setting up the equivalent circuits on the network calculator and have actually applied the faults in which they are interested. They have found that they thus obtain reliable results and their studies afforded a basis for the design of a capacitor potential device capable of giving a correct voltage ratio for short time operations as fast as one cycle.

The steady-state analysis may also be complicated when delta, residual, and star-connected burdens are on the same device. The delta burden involves the positive- and negative-sequence circuits, the residual burden involves the zero-sequence circuit, and the star burden involves all three. Through the concepts of symmetrical components, the performance of the device with respect to each burden can be determined and the criteria set up to obtain a design giving uniform results for all burdens. The paper describes in detail how this is accomplished.

E. L. Harder, P. O. Langguth, and C. A. Woods: The several discussers have added valuable comments and supplementary information indicative of the rather widespread interest in the transient performance of potential devices.

1. Mr. Langstaff brings out a very important point which deserves emphasis, namely that with normal-speed relays the transient performance is relatively unimportant because the relay operating time extends beyond the transient period.

2. Messrs. Laughlin and Blakeslee have indicated that installations of capacitor potential devices are being made very generally on their important line projects and it may be noted that this is generally true of all major transmission projects of recent date. These discussers have further emphasized the desirability for standardization of nomenclature. The functioning of the over-all device may best be viewed as a double transformation, the first consisting of a capacitance potentiometer and the second consisting of the transformer. The entire potentiometer comprising two sections which we have called the "stack capacity" and the "tap capacity" constitute the coupling to the power circuit. Hence, these terms seem more significant than the words "coupling capacity" and "auxiliary capacity."

3. That the complete analysis of the transient performance involves consideration of the specific relay performance as well as that of the device is well brought out in the discussion by Mr. Kennedy. He points out that the obtaining of frequencies other than normal would be objectionable for relays carefully tuned to normal frequency. It is our feeling that relays dependent upon system frequency being accurately maintained are to be avoided in any case in view of departure of system frequencies from normal during system disturbances. Mr. Kennedy also has suggested that the insertion of tabular data, which the average application man could use to determine whether or not his particular case would have trouble from transients, would be of interest. The method of determining the natural frequencies and decrements for any particular relay burden and device has been given and an example has been worked out in the section headed, "Transient Performance—Series Circuit". Also, the values for a number of specific burdens and devices have been given in the oscillograms and summarized in table II. A considerable amount of similar typical transient test information had been included originally in the paper but it was necessary to delete this information because of space limitations. Summarizing the steps involved in determining the transient performance in any particular case:

1. Determine the constants of the device for the particular adjustment and of the connected burden and reduced to an equivalent series circuit as shown in figure 2.

2. Determine whether oscillatory or nonoscillatory, based on whether R^2 is less or greater respectively than $4\,L/C$.

3. If nonoscillatory, the time constants should be determined from equations 35 and 36, the time to crest from 38 and the crest value or overshoot from 39. This is based on the primary voltage falling to zero.

4. In case the circuit is oscillatory the natural frequency would be determined from equation 41, the ratio of successive peaks or the decrement from 43, and the first peak in the case of pure resistance burden from 44.

For the more complicated burdens and connections the a-c network calculator provides the most convenient method of solution.

Mr. Kennedy has expressed surprise that the term Z_x could be ignored in the transient analysis. It is true that to be perfectly general this term should be included. However, for the device described the exciting impedance is very high compared with the tap-capacitor impedance. It is only when saturation occurs that this impedance would fall to low enough value to affect results. The specially designed transformers used with the devices described in the paper operate at flux densities sufficiently low that saturation does not occur even under transient conditions. Tests on complete three-phase devices substantiate these conclusions.

4. Mr. Higgins has presented an interesting circuit utilizing two damping resistors, one in parallel with the transformer secondary and the other in parallel with the burden. Early in our development an analysis was made of these possibilities and it will be of interest to show from the theory given in the paper the results to be expected. Considering a high-power-factor burden such as a pure resistance, it is evident that the connection of a second resistor in parallel will lower the total R of the circuit and as shown in equation 43 will increase the ratio of successive peaks, which is opposite to the desired effect. Also since R^2 is smaller compared with $4L/C$, the circuit tends to become more oscillatory than before. With pure inductive burden, damping resistance at this location will introduce loss in the resonant circuit and reduce the ratio of successive peaks. Obviously actual burdens will generally fall between these two limits, but our analysis has indicated that down to quite low power factors the net effect is unfavorable.

The resistance in parallel with the transformer secondary will exercise a pronounced damping effect on the resonant circuit since it is connected across the high-voltage point of this circuit. However, it will also make the impedance Z_{acx} shown in figure 2*d* of the paper a resistance-capacitance branch rather than nearly pure capacitance. As a result it cannot be neutralized by the reactance Z_{tr} and, therefore, the vector I_bZ (figures 3*a*, *b*, *c*) becomes relatively large. The resulting steady-state performance of the device is affected as it is no longer a "stiff device". Changes in burden cause relatively large ratio and phase-angle variations. This will be especially important when both star and residual burdens are supplied from the same set of devices. The star voltages, although adjusted correctly for balanced conditions, will be in error under fault conditions which involve residual voltage. This is explained in appendix II of the paper. These effects may be small enough so as not to be objectionable in some applications.

5. Mr. Powel has very nicely summarized the main points brought out in the paper.

Progress of the Art in Electrical Machinery—1934–39

THIS REPORT on the progress of the art in electrical machinery covers the five-year period from 1934 to June 1939.

D-C Machinery

There have been no radical changes in the design of d-c machinery for many years. Since the advent of the commutating pole, development has been almost entirely to extend the limits of performance along known lines.

There has been a slow extension of the speed of the machines, particularly the exciters and dynamometers. The speed of dynamometers both in revolutions per minute and peripheral velocity has been higher than that of the exciters. The reason for this is that although the dynamometers are all capable of operating at high speeds, in actual practice they run very little at the top speeds. For exciters, the peripheral speeds of the cores of machines in service have reached 13,000 feet per minute with 10,000 feet per minute on the commutator. One manufacturer is now building 3,600-rpm exciters having a peripheral of 15,000 feet per minute.

There is evidence for need of development of d-c motors which can be started across the line. At the present time, the practical limit of 230-volt compound motors is about 7 $^1/_2$ horsepower at 1,750 rpm and in the 550-volt motors, the compound-wound three-horsepower is about the limit. Shunt-wound motors that may be line-started are very much smaller. There seems to be a definite need for the extension of line-starting practice to larger machines as soon as designs will permit.

On the adjustable-speed motors, that is, motors whose speed is controlled by weakening the field, the present maximum ratio is six to one. Most adjustable-speed applications are served by a four-to-one range. Reversing planers and certain other special applications have been successfully served for several years by six-to-one speed range by field weakening.

The use of glass insulation is being tried on various applications for d-c motors. At the present time, there has been no report of any pronounced disadvantage in the use of this type of insulation.

Transformers

Insulation impulse tests have been established, and levels for guarantees and tests proposed for use by the industry. This work is probably one of the principal features for this period. It is not yet quite complete as levels for steep-wave-front testing have not been established.

The standardization of transformer ratings on the basis of temperature rise without reference to ambient temperature has been proposed and very generally accepted.

Considerable progress has been made in recommending additions to the material given in AIEE Standard No. 100 entitled "Recommendations for the Operation of Transformers," dated 1930. These additions include curves for short-time overloads (1) for recurrent conditions and (2) for emergency conditions ranging in time from a few seconds (short circuit) to several hours. As a rough guide for operating by oil temperature, oil temperature limits are given for various loads.

This work has resulted in the adoption of a pamphlet entitled "Guides for Operation of Transformers" which is to be incorporated as an appendix to the Proposed American Standards for Transformers, Regulators, and Reactors" to be published soon by the American Standards Association. The work on these operating recommendations is being continued in order to determine whether different recommendations should be made for transformers operated with expansion tanks or with inert gas above the oil level.

The question of the possibility of operating transformers at higher temperatures when excluding oxygen from the oil by the use of an inert gas cushion, or the use of an expansion tank (conservator) has been under discussion. Further consideration may show that by excluding oxygen from the oil, higher temperatures may be permissible.

Mercury-Arc Rectifiers

The use of the multianode metal-tank mercury-arc rectifier is well established in several fields. There are at present approximately 500,000 kw of this type of rectifier in operation on railway properties in America. The units vary in capacity from 500 to 3,000 kw and in voltage from 500 to 3,000 volts direct current.

The outstanding railway rectifier installations recently finished and put in operation include the San Francisco-Oakland Bay Bridge Railway, where 20,000 kw of rectifier capacity was installed for voltages of 600 and 1,200 volts direct current and capacities up to 2,500 kw per unit; and for the City of Philadelphia for heavy-duty subway service, consisting of two 3,000-kw 630-volt rectifiers.

In recent years, the mercury-arc rectifier was introduced in electrolytic plants. Some of the larger installations were for chlorine, sodium, and aluminum production. At present, there are in use in this country over 175,000 kw of rectifier capacity supplying this industry. One of these plants has 20 rectifiers with a total capacity of 55,000 kw. These were put in commercial service in the latter part of February 1938.

Due to the fact that a concentration of 55,000 kw of rectifiers in one substation became a major load of the supply network, it became necessary to reduce the influence of the harmonics on neighboring communication systems. In order to overcome this difficulty, an arrangement was used which provided phase displacement of each unit, by means of auto-transformers, by different amounts in order to increase the effective number of rectifier phases. The installation, considering all units as a whole, operates as a 60-phase system, and the harmonic currents generated by the rectifiers in the a-c network were reduced to such an extent that the effect of the rectifier load on the power and adjacent communication systems was practically eliminated.

Paper 39-135, prepared by the AIEE committee on electrical machinery, recommended by the AIEE committee on electrical machinery, and presented at the AIEE combined summer and Pacific Coast convention, San Francisco, Calif., June 26–30, 1939. Manuscript submitted April 24, 1939; made available for preprinting May 10, 1939.

AIEE Electrical Machinery Committee, 1938–39: C. M. Laffoon, *chairman;* J. L. Hamilton, vice-chairman; P. L. Alger, J. E. Clem, J. H. Cox, C. M. Gilt, I. W. Gross, M. S. Hancock, F. E. Harrell, A. P. Hayward, C. C. Herskind, F. Ellis Johnson, L. A. Kilgore, O. K. Marti, V. M. Montsinger, T. H. Morgan, S. H. Mortensen, F. L. Moser, C. A. Muller, J. R. North, F. D. Phillips, H. V. Putman, P. H. Rutherford, C. C. Shutt, J. B. Swering, H. D. Taylor, B. R. Teare, B. Van Ness, Jr., and G. A. Waters.

Subcommittees and Chairmen, 1938–39: Induction machinery, G. A. Waters; transformer, F. J. Vogel; rating of electrical machinery and apparatus, F. E. Harrell; synchronous machinery, H. D. Taylor; test code for fractional-horsepower motors, J. L. Hamilton; mercury-arc-rectifier, O. K. Marti; d-c electrical machinery, M. S. Hancock; insulation-resistance, J. B. Swering.

This illustrates an inexpensive means of reducing the effect of rectifier harmonics by utilizing the large number of anodes available in a large installation for increasing the number of phases.

Development work has been done toward perfecting the use of energized grids to obtain voltage regulation, and to obtain rapid extinction of the arc during abnormal conditions such as short circuits and arc backs. By applying a negative potential to the grids, current from properly functioning anodes may be blocked and prevented from feeding into a fault, and by the use of auxiliary electronic tubes, or high-speed relays, this type of arc extinction may be accomplished in the order of one cycle.

The need for heat exchangers to overcome the corrosion problem in steel-tank mercury-arc rectifiers has been eliminated for many cases by soldering or welding copper cooling coils to the tank walls. Of course, this method does not eliminate heat exchangers where the water available deposits a prohibitive amount of scale, necessitating straight tubes for mechanical cleaning.

The ignitor type of rectifier, or ignitron, constitutes the most radical departure from conventional practice in America during the past few years. Considerable attention has been given throughout the world to single-anode tank mercury-arc rectifiers, and the ignitron belongs to this class. This type of tube makes use of an ignitor which starts the arc in a tube by forming a cathode spot or a pool cathode at the beginning of each conducting period for a particular anode and permits the arc to extinguish during the nonconducting period. This type of operation has permitted the location of the anode directly over and relatively close to the cathode, with a reduction in the amount of shielding. This results in an appreciable reduction in arc voltage. Control of voltage, and arc extinction during faults, is accomplished by operating on small auxiliary thyratron tubes in the ignitor circuit, which control the time of firing.

Ignitrons are now in service in various industries. There are 13 units in mining service at 275 and 600 volts and in capacities from 300 to 500 kw. In electrochemical service, there are seven units at 280 and 600 volts and with capacities from 200 to 1,000 kw, and in railway service, there are two 600-volt 3,000-kw units. These latter have an anode rating equal to that of the largest multianode rectifier.

Recently, some units of permanently evacuated pumpless rectifiers have been installed, for lower-capacity requirements, at both 250 and 600 volts. Some of these are multianode glass-bulb mercury-pool rectifiers; some are metal-tank single-anode ignitrons; and others are metal-tank thermionic cathode phanatrons. These sealed-off rectifiers are attractive for small-capacity requirements because of the absence of vacuum-pumping auxiliaries. However, the need for periodic replacement must be balanced against objections associated with continuously operating vacuum auxiliaries.

Table I

Number	Kilovolt-Amperes	Kilowatts	Customer	Manufacturer*	Date Installed
2	25,000	20,000	Louisiana Steam Generating Co.	W	1938
1	29,500	25,000	Connecticut Light and Power Co.	W	1938
1	31,250	25,000	Gulf States Utilities Co.	W	1938
1	25,000	20,000	Kansas Gas and Elec. Co.	W	1938
1	37,500	30,000	Boston Edison Co.	W	1939
1	25,000	20,000	Metropolitan Edison Co.	W	On order
1	43,750	35,000	Iowa Power and Light Co., Des Moines	AC	1938
1	31,250	25,000	Central Illinois Public Service Co.	AC	1938
1	25,000	20,000	Southern Indiana Gas and Elec. Co.	AC	1938
1	25,000	20,000	Madison Gas and Elec. Co.	AC	1938
1	18,750	15,000	City of Springfield, Ill.	AC	1938
1	31,250	25,000	Central Illinois Public Service Co.	AC	On order
1	31,250	25,000	Public Service Co. of Colorado	GE	1937
1	28,571	20,000	United Power Mfg. Co.	GE	1937
1	25,000	25,000	Monongahela West Penn Public Service Co.	GE	1937
1	25,000	20,000	N. Y. State Elec. and Gas Corp.	GE	1938
1	50,000	40,000	Hartford Elec. Light Co.	GE	1938
1	25,000	20,000	Ohio Edison Co., Mad River	GE	1938
1	37,500	30,000	Potomac Edison Co.	GE	1938
1	25,000	20,000	Public Service Co. of N. H.	GE	1938
1	25,000	20,000	Public Service Co. of Okla.	GE	1938
1	42,857	30,000	City of Jacksonville, Fla.	GE	1939
1	28,571	20,000	Houston Lighting and Power Co.	GE	1939
1	31,250	25,000	Consolidated Gas Elec. Light and Power Co. of Baltimore	GE	On order

* W—Westinghouse Electric and Manufacturing Company; AC—Allis-Chalmers Manufacturing Company; GE—General Electric Company.

Turbine Generators

The two principal items of progress in turbine generators during the past few years are (*a*) the development of the two-pole 3,600-rpm unit for ratings required by the central-station industry, and (*b*) the application of hydrogen as the cooling medium.

The use of higher temperatures and pressures has greatly increased the range of capacities of the higher-speed units into the field formerly held by 1,800-rpm units or even of 1,200-rpm units.

The higher rotational speed makes it possible to use smaller physical dimensions and weights for the turbine. This simplifies the design and construction problems introduced by the use of high pressures and temperatures of the steam.

Large-capacity air-cooled, 3,600-rpm turbine generators on order or in service are listed in table I.

The advantages of hydrogen as a cooling medium for turbine generators are:

1. Reduced windage, friction, and ventilating losses, because of the low density of the hydrogen gas. The ventilating losses are proportional to the gas density. Full-load efficiency of the generator may be 0.6 per cent or more higher than for the corresponding air-cooled machine.

2. Increased output per unit volume of active material, because of the high heat-storage capacity, thermal conductivity, and heat-transfer coefficients of hydrogen. This advantage of hydrogen cooling makes it possible to build turbine generators for higher ratings than are possible with air cooling.

3. Reduced maintenance expense, because of the freedom from dirt and moisture.

4. Increased life of the insulation on the stator winding, because of the absence of oxygen and moisture in the presence of corona.

5. Reduced windage noise, because of the low density of the gas.

Hydrogen-cooled turbine generators either in service or in manufacture are listed in table II.

With operating experience on a number of units and over a considerable period of time at hand, the initial stage of development of hydrogen-cooled generators is passed. There will no doubt be minor difficulties to correct as time goes on, but these will be of no more serious nature than are to be found in air-cooled generators. It will also be possible to simplify considerably the generator and its attendant parts in future machines as greater experience is gained with this

Table II

Number	Kilovolt-Amperes	Kilowatts	Customer	Manufacturer*	Date Installed
3,600-rpm units					
1	50,000	45,000	West Penn Power Co.	W	1938
1	58,889	53,000	Consolidated Edison Co. of N. Y., Inc.	W	1938
1	58,750	50,000	Philadelphia Elec. Co.	W	1938
1	43,750	35,000	Cincinnati Gas and Elec. Co.	W	1938
1	81,250	65,000	Consolidated Edison Co. of N. Y., Inc.	W	On order
1	43,750	35,000	Pa. Power Co.	W	1939
1	43,750	35,000	Columbus and Southern Ohio Electric Co.	W	1939
2	43,750	35,000	Georgia Power Co.	W	On order
1	43,750	35,000	Pa. Elec. Co.	W	On order
1	18,750	15,000	Wis. Elec. Power Co.	AC	1938
1	31,250	25,000	City of Lansing, Mich.	AC	On order
1	31,250	25,000	Dayton Power and Light Co.	GE	1937
1	50,000	40,000	American Gas and Elec. Co., Logan, W. Va.	GE	1937
2	66,667	60,000	American Gas and Elec. Co., Windsor station	GE	1— 1939 1—On order
1	58,889	53,000	Consolidated Edison Co. of N. Y., Inc.	GE	1938
1	37,500	30,000	New Orleans Public Service Co.	GE	1939
1	55,555	50,000	Public Service Elec. and Gas Co.	GE	1938
3	43,750	35,000	Consumers Power Co.	GE	On order
1	28,125	22,500	Ind. and Mich. Elec. Co.	GE	On order
3	50,000	40,000	Pacific Gas and Elec. Co.	GE	On order
1	50,000	40,000	Virginia Elec. Power Co.	GE	On order
2	50,000	40,000	Duke Power Co.	GE	On order
2	62,500	50,000	Public Service Elec. and Gas Co.	GE	On order
1	62,500	50,000	Philadelphia Elec. Co.	GE	On order
1	81,250	65,000	Consolidated Edison Co. of N. Y., Inc.	GE	On order
1,800-rpm units					
1	75,000	60,000	Duquesne Light Co.	W	1938
1	176,470	150,000	Chicago District Elec. Generating Corp.	GE	1937
1	81,250	65,000	Cincinnati Gas and Elec. Co.	GE	1938
2	68,750	55,000	Ford Motor Co.	GE	1939
1	60,000	54,000	Ind. and Mich. Elec. Co.	GE	On order
1	100,000	80,000	Central N. Y. Power Co. (Oswego)	GE	On order

* W—Westinghouse Electric and Manufacturing Company; AC—Allis-Chalmers Manufacturing Company; GE—General Electric Company.

type of machine. Cost of supplying hydrogen gas is very low, and it has been the experience in most stations that the additional attention on the part of the operators as compared to that for an air-cooled machine is very small. Hydrogen cooling will probably be adopted more and more for units of 30,000 kw and above where the additional cost of the gas-tight housing and gas control can be justified economically.

Synchronous Condensers and Motors

A novel synchronous condenser rated 25,000 kva at 3,600 rpm (W)* has been built for the American Gas and Electric Company with hydrogen cooling, and excitation from an ignitron rectifier. A 50,000-kva 50-cycle 600-rpm hydrogen-cooled synchronous condenser (W) was furnished the Southern California Edison Company. The design of this condenser permits operation at 60,000 kva and 60 cycles. Two 30,000-kva 1,200-rpm hydrogen-cooled synchronous condensers (GE)† were supplied to the City of Seattle and the Ohio Power Company, respectively, during the year, and very recently a 60,000-kva, 600-rpm hydrogen-cooled condenser (GE) has been ordered by the City of Los Angeles. Air-cooled condensers (AC)‡ rated at 15,000 kva, 900 rpm, and 20,000 kva, 720 rpm were furnished the Memphis Power and Light and the Illinois Northern Utilities Company respectively. A 25,000-kva condenser (W) was installed at the Massena plant of the Aluminum Company of America in 1937. A similar 15,000-kva air-cooled condenser (W) is now on order for the Florida Power and Light Company.

* Westinghouse Electric and Manufacturing Company.

† General Electric Company.

‡ Allis-Chalmers Manufacturing Company.

Three vertical-shaft synchronous motors out of an order for six were installed for the Metropolitan Water District of Los Angeles, rated 12,500 horsepower, 450 rpm (W), built for exceptionally severe starting duty; these are similar to machines rated 9,000 horsepower, 400 rpm (GE) and 4,300 horsepower, 327 rpm, (AC) previously installed on the same water supply project. In marine work, two turbine-electric tankers of unusual interest were placed in service by the Atlantic Refining Company, the *J. W. Van Dyke* and the *Robert H. Cooley*, each with a main-drive synchronous motor rated 5,000 horsepower, 90 rpm supplied with power by a turbine-generator of 4,500-kw capacity (GE), the output of the generators being used when in port for driving pumps for rapid loading and unloading.

Electric Couplings

Electric couplings are now coming into general use in geared ship-propulsion installations to provide the necessary flexibility to protect the gears from torsional vibration from the engine. In addition, they limit shocks in the system by having a definite maximum torque which they will transmit, this torque being independent of speed. They also can be disconnected instantaneously by interrupting their field current.

In construction, the form generally used consists of a salient-pole field member excited by direct current and a secondary member similar to that used on an induction motor. The secondary rotates with the field except for a small slip.

At the present time, one tanker has been equipped with two 700-horsepower (Elliott) couplings and there are on order 68,000 ship horsepower (W) in 24 couplings for use on vessels being built for the United States Maritime Commission.

Induction Motors

There has been a material increase in the number of high-speed induction motors built for high-pressure pump applications. The ratings of two-pole 60-cycle induction motors have reached 2,500 horsepower.

The noise level of high- and moderate-speed motors has been reduced to the point where it is well below that of a modern power house.

Explosion-resisting motors of cast or fabricated construction are now being built for ratings up to 600 horsepower, 3,600 rpm. Glass insulation is playing a part in the development of these motors.

The completion of two 1,000-horsepower 3,000-rpm totally enclosed motors (GE), ventilated by carbon-dioxide gas circulating through surface coolers, marks an important new trend in this field. This design provides security against explosion risks in sizes larger than can conveniently be made of the heavy explosion-resisting construction.

Frequency Converters

A 20,000-kw variable-ratio frequency changer (GE) of the Scherbius type built during the year was unusual in having the Scherbius equipment on the 60-cycle end. The induction machine of this set is a wound-rotor type with 24 poles, rated 27,000 kva, 300 rpm, 13,800 volts,

and is designed for 0.8 power factor over-excited operation with a slip adjustable over a total range of one cycle. A 60,000-kva, 50–60 cycle 600-rpm hydrogen-cooled frequency changer (W) was built for the City of Los Angeles and installed late in 1936.

Water-Wheel Generators

Most of the available water-power sites which are economically important from the standpoint of electric-power production and disposition alone have been developed. The majority of the hydroelectric developments that are being undertaken at the present time are justified economically for the production of electrical energy only when considered in connection with irrigation, flood control and navigation, or a combination of these factors. Undertakings of such broad scope are necessarily of a public nature and consequently have been carried on as complete or partial-public or governmental enterprises.

The principal improvement in the hydraulic turbine has been the development of the adjustable-blade propeller to improve the efficiency performance of the turbine under different water flow conditions. No major changes have been required or made in the design of generators driven by this type of prime mover.

A large number of hydraulic turbine driven generators has been purchased or placed in service. Two more Boulder Dam units rated 82,500 kva, 180 rpm (GE) were tested and placed in service, and two others (W) were built and ready for installation. The City of Los Angeles has purchased two additional 82,500-kva units (W) for installation at Boulder Dam. At Bonneville Dam two 48,000-kva 75-rpm generators (GE) were installed, and two more rated 60,000 kva (GE) were on order. For the Tennessee Valley Authority developments, two 40,000-kva 81.3-rpm units (W) went into service at Pickwick Dam; three rated 27,000 kva, 69.2 rpm (GE), under construction for Guntersville, have the distinction of having the largest diameter and highest overspeed of any generator so far designed of the overhung type; for the Hiwassee Dam, one 64,000-kva 120-rpm unit (W) has been ordered; and three units of 30,000 kva 75 rpm (AC) have been ordered for Chickamauga Dam. Interesting units for export include two horizontal machines of unusually high speed, rated 10,118 kva, 500-rpm, 25 cycles (GE) built for the government of Mysore, India, and three vertical machines rated 70,000 kva, 125 rpm (W), on order for the Sungari River development in Manchukuo. Among recent orders are the three 108,000-kva 120-rpm machines (W) for Grand Coulee, these having larger dimensions than the famous Boulder Dam units; and four rated 75,000-kva, 120 rpm (GE) for the Shasta development of the Bureau of Reclamation. Two 34,000-kva 120-rpm units (GE) and two 34,000-kva 120-rpm units (W) are under construction for Santee Cooper. Four 16,000-kva, 150-rpm units (W) for Grand River have been shipped. Four 20,833-kva $138^1/_2$-rpm units (W) for Appalachian Electric Power Company have been shipped. One 27,500-kva 120-rpm unit (W) has just gone into service on the property of Anglo Newfoundland Development Company.

Electrical Engineering and the Petroleum Refiner

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THE object of this discussion is to present a brief history of the use and development of electric power in the oil-refining industry and to indicate how refinery design and operation have been affected by recent developments in electrical engineering.

An oil refinery consists of equipment for the receipt and storage of crude oil, apparatus for converting it into salable petroleum products, and additional storage and distribution facilities for the finished products. The first and last of these classes of equipment are composed largely of tanks, piping, and pumps. In the second category is the refinery proper, which may be compared to a shop containing many machines, the refinery being composed of various processing units, each of which performs a definite task upon a certain crude or previously processed feed stock. The most important of the units carry out the process of fractional distillation, obtaining numerous products ranging from heavy tar or coke to light highly volatile hydrocarbons. Fractionation is often combined in a given unit with the supplementary processes of cracking, polymerization, etc.

A typical distillation unit consists of one or more furnaces, a battery of pumps, fractionating towers, smaller pressure vessels, heat exchangers, condensers, etc. Many of these units operate under pressure and temperature conditions comparable to those encountered in modern boiler plants.

Other units are required to condition the products of the fractionating process for sale; these consist of stabilizer plants, chemical treating plants, blending units, dewaxing plants, etc. A third type of unit is the by-product plant which may produce anything from insecticide to compounds used in cable insulation. In addition to the refinery proper there must be auxiliary plant equipment for supplying steam, electric power, compressed air, repair and construction services, office facilities, etc.

Safety Precautions to Be Observed

The refining of petroleum involves the safe handling of inflammable and corrosive liquids and gases. The major part of refinery electrical equipment is therefore designed to be suitable for use with equipment performing such operations. Suitable electrical equipment is approved by the Underwriters' Laboratories for use in what is termed class 1, group *D*, hazardous locations.

Apparatus, to be classed as explosion resisting, must be designed so that it is not possible for an internal ignition of explosive vapors to be propagated to the outside atmosphere. Sturdy cases with ground-joint heavily bolted flanged covers are required or the apparatus must be deeply immersed in suitable steel tanks filled with oil. Screwed joints must have at least five tight threads. Conduit entrances to spark-producing apparatus must be sealed with compound in an approved sealing chamber to prevent propagation of an explosion along the conduit

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system; long conduit runs are sealed at intervals for the same purpose.

The presence of sulphurous gases, furnace smoke, and salt air (since many refineries are located on seacoasts) makes it necessary to use porcelain insulators of much higher rating than the service voltage—15,000-volt insulators are commonly used for 2,300-volt service. In addition, all electrical apparatus must be protected to the greatest possible degree against corrosion, or designed of suitable materials to withstand the corrosive effect.

Type of Load

The refinery load is one that usually offers a unique opportunity for economical power generation. Waste refinery products are generally available as a cheap fuel in both liquid and gaseous forms, the need for process steam makes possible an economical station heat balance even with a restricted supply of condensing water, the use of dual steam-electric-driven pumps and other equipment furnishes a means of adjusting the heat balance, and finally and perhaps of most importance, the high percentage of the generated power used for driving synchronous motors and fully loaded induction motors which operate for long periods without shutdown makes for high load factors and high power factors. Continuous operation of a refining unit for 30 days is not unusual and runs of six months or longer are expected for some processing operations. There are seasonal variations in total load on the generating equipment due to seasonal variations in demand for various products (see figure 1), however, these are not ordinarily so great that an economical heat balance cannot still be maintained. Daily load variations are very small since the lighting load is small and the power load is continuous.

Steam and Compressed Air

Process steam is generally supplied to the refinery from the boiler plant at pressures in the vicinity of 125 pounds gauge, and is used in considerable quantities for supplying distillation heat, for oil-burner atomization, stripping operations, and for gas freeing of equipment. Certain engines and turbines are steam driven from the 125-pound mains for driving fans, pumps, and compressors, especially in older units. These units usually exhaust to the low-pressure steam main at about 10 pounds pressure. Such low-pressure steam is used in heating buildings and heavy-oil storage tanks, and is also employed to maintain a low viscosity in pipe lines circulating heavy oil through the refinery by carrying a small steam line next to the oil line under an insulating jacket. Steam is also used to some extent for fire protection.

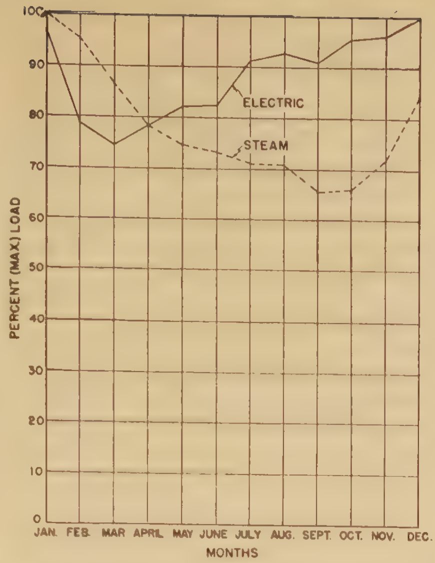

Figure 1. Monthly variation of steam and electrical load in a refinery

A supply of compressed air is necessary for the pneumatic tools used in refinery maintenance. At every "turn-around" or shutdown period, the tubes of tubular furnaces are cleaned by air-driven tools. Drills, grinders, tube-expanders, jack-hammers, and riveters, are in use. The necessary compressed air is supplied in the typical refinery by synchronous-motor-driven compressors of large size.

Electric Power

The introduction of high-pressure high-temperature steam equipment for industrial power-plant application and the development of the high-back-pressure turbine made refinery engineers more conscious of the merits of electric drive, especially from the standpoints of economy of operation and saving of space. The type of mechanical equipment used in refineries then underwent major changes as manufacturers of this equipment were called upon to develop new and entirely different apparatus than was used hitherto.

The high-back-pressure turbine was much in demand when first introduced as it supplied the large quantities of medium-pressure steam for driving slow reciprocating pumps and other relatively inefficient processing equipment. Then, as the opportunity occurred to replace worn out and inefficient steam equipment with electric drive, the need for large amounts of medium pressure steam decreased and correspondingly, the requirements for electric power increased with the result that use of condensing turbine again became practicable. However, the high-back-pressure turbine was soon followed by the very flexible bleeder-condensing turbine so that today the refinery engineer may select from a wide range of equipment to give him an efficient power plant tailored to fit the scheme of operation of his particular refinery.

The most popular generating voltage is 2,400 volts because it has a wide economical range of uses without transformers together with very good distribution characteristics. Other voltages such as 6,900 and 13,200 volts are being used in individual cases for specific reasons such as long-distance distribution which might be necessary for a very large refinery.

With the increase in power used at 2,400 volts, a new class of switching equipment had to be developed to handle safely the increased capacity generated at what today is considered a low voltage. This equipment had to embody the safety principles of utility-company equipment and yet be reasonably low in first cost. Such equipment is the present-day medium-interrupting-capacity short-time high-current-carrying-capacity high-speed oil circuit breaker with high-speed relays, all factory assembled in dead-front steel cubicles. Still a further development necessitated by the high currents in the present large low-voltage generating station was improvement in bus design, so that electrical engineering borrowed from structural practice the angle, channel, and box designs that we have today. The larger stations have main and synchronizing busses with reactor protection between generator bus sections or bus sectionalizing reactors to limit short-circuit currents to a reasonable figure in order to make use of economical types of switchgear.

Distribution System

A refinery distribution system is required to supply substations that are located to serve the different operating areas or load centers. In a large refinery, units are continually being added to or withdrawn from the refinery system so that the load centers are continually changing. The basic distribution scheme therefore must have maximum flexibility to meet the ever-changing requirements.

Depending on the size and layout of the particular refinery and its power sources, loop, radial, or combination loop-radial systems are used for the high-voltage

distribution. The processes are such that a definite closely knit load center can be established for each unit, thus tending to simplify the secondary-distribution problem.

Overhead lines have been widely used for high-voltage distribution, but refineries are now following the modern trend to underground construction. This is highly advantageous from the standpoints of safety, reliability of service, and clearing the air to allow freedom in fighting fires, moving cranes, etc. Overhead distribution is retained where the economics of the situation so dictate. Substations are required to supply high voltage directly to feeders for large motor-driven compressors and pumps, to transformers for 440-volt power distribution to small- and medium-size motors, lighting transformers, and numerous miscellaneous services.

A typical substation consists of a small building and adjoining fenced-in transformer enclosure.

Substation switchgear in older installations was of the pipe-frame and panel type with panel-mounted instruments and controls and oil circuit breakers pipe-frame mounted behind the panels. Such equipment is being superseded by metal-clad and steel-cubicle-type switchboards in new construction; advantages being greater safety to personnel, greater reliability due to enclosure of bus bars and control circuits, and smaller space requirements.

Motors

Advances in pump design have been of great importance to refinery power engineers since this type of load far exceeds any other. Slow-speed reciprocating pumps with high steam consumption have been replaced to a great extent by high-speed space-saving centrifugal pumps with efficient direct-coupled motor drive.

When such pumps were first used in refineries, they were driven by open motors and the motors and pumps were separated by fire walls. Fire walls do not completely eliminate the fire hazard in all cases and are expensive and inconvenient in any case. The explosion-proof totally enclosed motor has been developed until today this type of motor is standardized in sizes up to 350 horsepower. It is reasonable in first cost and the maintenance on this type is far less than was experienced with the open type.

The extension of explosion-proof motors to include gearmotor and close-coupled motor and pump units has substantially contributed to the increased use of electricity.

Improvements in bearings, fans, and insulation have been applied to explosion-proof motors to enable them to operate at high temperatures in corrosive refinery atmospheres. These motors, being completely enclosed, can be mounted outdoors, thereby eliminating expensive pump houses.

Refinery experience indicates that for greatest economy individual motors should be low voltage (440) up to 75 horsepower and high-voltage above that rating where 2,400-volt distribution is used. When the distribution system is at a higher voltage the horsepower dividing line is, of course, higher.

The uninterrupted operation of essential pumps while the unit is "on stream" is of extreme importance to the refinery operator. In this case a dual drive is frequently used, that is, the centrifugal pump has the impeller shaft extended through both ends of the casing, one end being coupled to a motor and the other end to a steam turbine. If the motor full-load speed is 3,550 rpm, an automatic valve would be set to admit steam to the turbine at about 3,500 rpm. Should there be a power failure or other fault in the electric drive the turbine would automatically take the load until the motor could be again brought into use.

Individual enclosed induction motor units as large as 1,250 horsepower at 3,600 rpm have been developed for use in refining areas, the enclosures are of heavy steel plate, and cooling is accomplished by means of water coils mounted within the enclosures. The enclosures are air-tight except for the shaft opening and are filled with inert gas at a pressure higher than atmospheric. The use of such motors is being extended to slightly or occasionally gaseous areas by omitting the inert-gas protection.

Synchronous motors are used in refinery work to a considerable extent for driving reciprocating compressors. These are used for air, refrigeration, and hydrocarbon gases.

The ease with which low-speed salient-pole synchronous motors may be designed and operated is the chief reason for their selection for compressor drive. In many instances the motor is installed between cranks of duplex machines in a manner analogous to the installation of shaftless induction motors in power tools, giving a valuable saving in space together with desirable mechanical characteristics. Compressor motors are usually large enough to require connection to the refinery high-voltage system but are not so large as to prevent full-voltage starting.

Where inflammable gases are handled or where refrigeration machinery is located in proximity to petroleum vapors, the motors are protected by fire walls or enclosed in an airtight steel casing with cooling air brought in through a duct from a gas-free area. Air is forced through the duct with an explosion-proof motor-driven blower having its starter interlocked with the compressor motor starter so that fresh air is supplied to the compressor motor before it can be started.

Motor Control

To obtain widest benefits from the previously discussed motor developments, it was necessary to obtain starting equipment especially designed for refinery service. Small low-voltage motors use standard air-break motor starters enclosed in cast-iron explosion-proof housings. Larger low-voltage motors are controlled by deep-oil-immersed starters of the across-the-line type. Satisfactory relays of both thermal and magnetic types have been developed for use under oil so that such equipment includes all features of non-oil-immersed equipment. Since the refinery distribution system is designed to carry large blocks of power, low-voltage motors are line starting except for a few of the largest sizes in refineries using distribution voltages above 2,300. Such starters are considered special.

The latest practice in motor control requires an air circuit breaker of the "arc dissipating" type in an explosion-proof housing at the motor branch junction. This breaker is depended upon for short-circuit protection and also serves as a disconnect.

An alternate practice is the use of oil-immersed starters combined in the same enclosures with oil-immersed fused switches. The necessary fuses are individually air sealed to prevent oil from interfering with their proper operation.

Since high-voltage motors are fed directly from a substation, the motor control equipment is usually located in the substation and is installed as a component part of the substation cubical switchgear. Approximately 50 per cent of these starters are required to be reduced-voltage type. Since such switchgear is required to have up to 50,000 kva interrupting capacity, the starter contactors are similar to modern oil circuit breakers in design. Remote push-button control is also used with these starters. As a late development the high-voltage starters are being constructed explosion re-

sisting for certain locations, such starters have oil-tight circuit-breaker-type tanks and open-air-type control equipment under a diving bell immersed in oil.

The necessary breakers and starters for all the motors, other than high-voltage motors, in a given refinery unit are usually grouped in a switch house and mounted upon racks. The switch house may be a simple roofed structure without sides, usually enclosed in chain-link fencing. The starters are push-button operated from explosion-proof push-button stations located at the motors and/or in the unit control room.

Instruments

For proper operation, the temperature at a multitude of points in the unit must be indicated at the unit control house so that liquid flow in various lines may be adjusted to maintain process requirements. To observe temperature conditions at the hundreds of necessary points and to correlate this information at necessary intervals would be a Herculean task in itself were it not for the use of recording pyrometers. Resistance bulb thermometers are in limited use but the majority of temperatures are measured by iron-constantan thermocouples. These and other types of instruments are motor driven. Instruments which may be rated explosion resisting are a current development.

While the total electric load developed by such instruments is not large, the instruments of an oil refinery do represent a problem in maintenance and in investment cost.

Automatic regulation of oil flow in certain lines in accordance with unit temperature conditions is obtained from instruments. This requires the use of electrically operated valves ranging in size from fractional-inch solenoid valves to large-size motor-driven valves.

Shops

Oil refineries are usually equipped to maintain and repair equipment. The extent to which repair equipment is installed depends in a large degree upon the location of the refinery and the availability of adequate industrial facilities in the vicinity.

Where the quantity of the work permits, a refinery will have foundry, boiler, machine, blacksmith, carpenter, electrical, instrument, and pipe shops, all of which require electrical power. This load is supplied by 440-volt three-phase lines.

Welding

In recent years, following improvements in welding technique, the scheme of certifying approved welding personnel, and the application of radiography, the use of welding in the oil industry has increased rapidly and we now have welded tankage, pressure vessels, piping for pressures up to 1,500 pounds, structures, pipe supports, etc. Welding is also used for applying stainless-steel linings to pressure vessels. The proper technique has been developed for welding the various chromium and nickel steel alloys which are commonly used for refinery piping. At present there appears to be no phase of refinery construction to which welding may not be applied. Refineries are now commencing to install complete systems of three-phase 440-volt welding outlets for operating portable motor-generator welding sets. These outlets are of explosion-proof construction having a switch (or circuit breaker) and interlocked receptacle. Refinery metal-working shops are usually provided with welding equipment.

Lighting

On most installations less than five per cent of the refinery load is composed of electric lighting. Lighting fixtures for use in processing areas are of the vapor-proof type with heavy glass globe and guard. Anodized-aluminum reflectors are used with such units when installed on the top level of structures, platforms, walkways, etc. Floodlights are installed on the equipment structures to illuminate the general ground areas in the immediate vicinity of the units.

Modern refinery design calls for the following lighting intensities:

Location	Foot-Candles
Control rooms	10 to 15
Pump rooms, switch houses	6 to 8
Main operating platforms	6 to 8
Yard areas and ordinary platforms	2 to 4

These intensities have tended to make work and maintenance around the units safer. This would not have been possible but for the fact that manufacturers developed suitable switches, plug receptacles, and conduit fittings.

Miscellaneous Power Use

The larger refinery units use oil- or gas-fired furnaces to heat the feed stock; however, in the specialty products field, units and quantities are small and electric heating equipment is applied to certain of them, presenting another 440-volt load. Isolated locations where steam is not available may require the use of electric heat.

A great many refinery instruments are connected by means of tubing to the various pipes and vessels. It becomes necessary especially during cold weather to heat certain of these instrument lines to keep their contents fluid; this may be done by wrapping the interconnecting tubing with electric heater cable. The instruments themselves are similarly protected by heater cables where necessary.

Long pipe lines and particular operations sometimes require cathodic protection. In the case of pipe lines, power must be supplied to cathodic protection units at intervals along the lines which adds distribution difficulties. Cathodic protection of boiler-house equipment and condensers is of standardized type.

Summary

The use of electricity in refineries has increased tremendously in the last decade; this increase can be primarily traced to:

1. Development of equipment that is suitable for use in refinery atmospheres.
2. Development of improved mechanical equipment.
3. Development of generating equipment of industrial size having suitable operating economies.
4. General advance in the engineering arts.
5. Development of increasingly complex refinery processes.

Discussion

Everett E. Thomas (General Electric Company, Schenectady, N. Y.): Mr. Weeks and associates have prepared a timely paper for drawing attention of people in the electrical industry to requirements for the application of electrical power in oil refineries. They are to be congratulated for this work which should benefit all who are interested in refinery electrification.

Methods of finding and producing crude oil, as well as progress in processes for refining it into commercial products, have interested me during the past decade and my interest grows as I become better acquainted with the oil industry. My close contact with power-application problems in the crude-oil industry has given me considerable respect for explosive and hazardous conditions to be met by proper design and application of electrical equipment for safer operation in gaseous areas.

Up to about 15 years ago, some refineries installed standard open-type motors with control in gaseous areas by placing them in

an air-conditioned room and projecting the motor shafts through a fire wall to the driven units while most refineries used electricity only for lights and for power in nongaseous areas. This situation prevailed until the development of explosion-proof motors and associated equipment made it economical and advisable to electrify processing apparatus. Also, substitution of a few tube stills for many shell stills called for much more power and much less low-pressure process steam. These conditions gave a decided impetus to practically complete electrification in crude-oil refineries.

As early as 1918, the electrical manufacturers began to realize the need for motors for explosive conditions in various industrial plants and the Underwriters' Laboratories tested an especially built motor later to determine the construction features really needed to meet hazardous conditions. Some 50-horsepower and 75-horsepower wound-rotor fan-cooled motors involving explosion-proof features were built for Russian oil-field drilling rigs as early as 1922. Later, a line of fan-cooled explosion-proof squirrel-cage motors up to about 50 horsepower was available and, as experience and knowledge increased, the line was rapidly extended so that at the present time motors up to 400 horsepower with "label" and larger without "label" are available.

Mr. Weeks and associates have included a discussion of individual enclosed induction motors. Economical and physical limitations of the explosion-proof construction prevent its use at the present state of the art in motors which are comparatively large either because of high rating as in case of hot oil pumps or low speed as for compressor drives. Inert-gas-filled construction has greatly extended the field of application in hazardous areas and is believed to be an outstanding contribution of the electrical manufacturers to refinery electrification. About nine years ago, there were built some 100-horsepower low-speed synchronous motors of totally enclosed fan-cooled construction and filled with inert gas under slight pressure for operation in a gaseous location. These motors were mounted on the crank shafts of reciprocating compressors.

Recently, an installation for driving hot oil pumps has been made using 1,000-horsepower 3,000-rpm induction motors of inert-gas-filled design and employing built-in heat exchangers in which water is used for cooling the inert gas. In the larger sizes, this substitution of water cooling for fan cooling results in a smaller and less expensive motor and is comparable in size to open-type motors. For nonhazardous areas where enclosed motor construction is required, several of the surface-cooler motors in larger sizes have been installed using air instead of inert gas. As compared to enclosed ventilated synchronous or induction motors, this has advantages of eliminating air ducts and, also, eliminating problems of supplying quantities of clean air.

Dual drives imply use of motors and steam turbines of same capacity. One modification is to use a turbine of about half the capacity of the motor for starting "on stream" and for emergency service to prevent coking in case of electrical power outage.

The trend of underground-cable construction for distribution involves suitable duct ventilation not only for dissipation of heat but to prevent accumulation of refinery gases in the duct work.

The fact that about half of the refinery load requires motors large enough to warrant using 2,200-volt design has caused general adoption of 2,400-volt generation and distribution. Employment of 4,000-volt wye generation and transmission may be considered initially since distribution expense would undoubtedly be reduced for large blocks of power and the larger motors can still be designed for this voltage but only for use without "labels" at this time since the Underwriters' Laboratories feel that there are some questions to be settled which include corona effects. It may even be found uneconomical in the long run to distribute the increasingly large blocks of power at either 2,400 or 4,000 volts for a distance of more than a few thousand feet, in which case 6,900-, 11,500-, or 13,800-volt generation for distribution to transformer substations located near the various load centers would be the solution. It is desirable to restrict these higher voltages to nonhazardous areas.

Short-circuit rupturing capacity of all power-control devices should be checked against initial and ultimate requirements. System growth makes it imperative for the user to check suitability of these devices from time to time. Frequently, 2,200-volt control requires protection which may be provided by use of group feeder reactors. The 440-volt control should be checked for short-circuit capacity even though its feeders may have considerable impedance.

Use of the synchronizing bus scheme in power stations is an effective way to provide protection for circuit breakers by means of current-limiting reactors. From 10,000- to 15,000-kw in steam-turbine generation at 2,400 volts may be the limit without resort to some scheme of short-circuit-current limitation as otherwise the initial short-circuit-current inrush becomes too great for conservative application of commercial circuit breakers. This limit is modified by pump-back from synchronous motors. The same breakers can be used on larger systems of higher voltage because the initial current is reduced with the increase in voltage. This means that the one-second rating of the breaker, which is a measure of its thermal and/or mechanical strength, becomes the limiting feature rather than its rupturing capacity at lower voltages. Hence, proper choice of voltage is a matter for close scrutiny with respect to the short-circuit capacity of available control and its relation to the over-all economics of the distribution system, including possible future growth.

An important recent development is the use of silver-coated contacts on devices and bus joints to minimize the effects of oxidation. Oxides on copper contacts must be wiped off frequently to prevent overheating if these contacts are fully loaded. Silver contacts do not overheat for normal duty but usually require arcing tips to prevent burning the silver.

Skimming or topping plants require about $1^1/_2$ horsepower-hours per barrel of crude oil and the cracking plant about 3 horsepower-hours. A complete refinery requires about $5^1/_2$ horsepower-hours per barrel of crude oil. There are about 460 active oil refineries in this country, and they represent throughput of 3,300,000 per day. Computations based upon these figures show approximate connected horsepower to be 1,800,000 and this includes 700,000 horsepower for electric motors. Evidently, there is much left to be done toward further electrification in crude-oil refineries.

G. R. Weeks, H. W. Giesecke, and C. M. Lathrop: Mr. Thomas' discussion is an interesting supplement to the paper. Alternate schemes for using dual-driven pumps have been presented; it should be made clear that considerations of economy and refinery setup determine whether the turbine unit of a dual-driven pump should have full or partial capacity. Dual drive is usually applied only to the largest or most important pumps of a unit. Unit charging pumps furnish the most conspicuous examples of dual drive. Small pumps are generally installed in duplicate with the spare unit arranged for steam drive. Where the unit is of large size and the refinery steam supply is ample, it is advisable in most cases to have full-capacity turbines for dual-driven machines in order to continue uninterrupted operation of the unit in case of electrical-power failure. Where the steam supply is limited or where the function or size of a unit is such that its shutdown in case of more than momentary power failure is not a serious matter, the selection of half-capacity turbines is warranted.

As to the choice of voltage for refinery distribution systems, it may be pointed out that an organization operating more than one refinery derives considerable benefit from selecting a voltage that can be commonly used by its refineries and that, at the same time, corresponds to general industrial practice; 2.4 kv is unrivalled in this respect.

Aside from designing for maximum safety, reliability of service must be considered above other factors in laying out an electrical system for a refinery.

It is felt that wye- or delta-connected rotating machinery is equally suitable for refinery use; however, there are reasons for recommending that systems operate ungrounded and that transformer banks consist of delta-connected single-phase units. The ability to operate on open delta up to the thermal capacity of the transformers is valuable in case one of a bank of transformers must be removed from service. Since a large margin of safety in insulation is usually built into refinery equipment and since the distribution voltages are comparatively low, the effect of abnormal voltage disturbances that may arise in ungrounded systems is considered to be slight. With an ungrounded system, operation of circuit breakers and shutdown of machines is avoided in most cases of momentary single-line faults due to lightning or accident.

The authors' experience covers one large refinery which uses 440- and 6,900-volt distribution. No difficulty has arisen here in obtaining motors of all required types and although 6,900-volt control equipment is somewhat special it is not comparably more expensive than 2,400-volt equipment. Such equipment consists of cubicle or panel and frame mounting of oil circuit breakers and accessory equipment. Where distribution at higher voltage is required the use of transformer substations, as Mr. Thomas suggests, is unquestionably indicated.

High-Capacity "Hydro-Blast" Circuit Breaker for Central-Station Service

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Synopsis: The increasing demand for oilless circuit breakers has resulted in a number of contributions in that field. Outstanding among these from the standpoint of interrupting capacity at generator voltages is the "hydro-blast" circuit breaker, which has been developed in ratings up to 1,500,000 kva. This breaker has the feature of complete interchangeability with the standard *H*-type oil circuit breaker and thus combines all of the well-known advantages of that type with the total absence of inflammable material. This paper describes in detail the construction and operation of the 500,000-kva hydro-blast circuit breaker for central-station service, several of which have been in service for over half a year.

WHILE the oil circuit breaker has for many years given a very good account of itself in the United States, there has nevertheless been a gradually increasing interest in the elimination of inflammable liquids from circuit breakers as well as from other electrical apparatus. While not ordinarily thought of as a good insulator, water has a much higher dielectric strength for short periods than is commonly appreciated, and could therefore be expected to be effective in interrupting an arc. From the standpoints of noninflammability and availability, of course, it is very attractive. An investigation was therefore inaugurated some time ago looking toward the development of a practical breaker using water as the interrupting medium.

Two requirements of primary importance in such a device are that the water should not be subject to continuous dielectric stress in either the closed or the open position of the breaker and that all parts coming into direct contact with the water be carefully selected in order to eliminate corrosion in connection with these parts. These requirements are admirably satisfied in what has been known for many years as the *H*-type breaker in which each of two breaks per phase takes place in a small separate tank, to which the liquid is confined. The major insulation is air and the corrosion problem is simplified by the fact that all major moving parts, except for a part of the contact rods themselves, are outside of the pots and thus kept away from the water.

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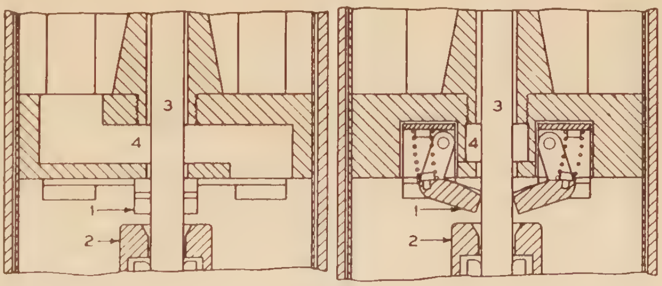
The authors wish to express their appreciation of the co-operation furnished by many individuals, without which the success of this development would have been impossible. Within the General Electric Company, valuable suggestions have been contributed by members of the large-oil-circuit-breaker engineering section and by the staff of the short-circuit testing laboratory, while investigations in the Philadelphia works laboratory have contributed very largely to the choice of materials. The Philadelphia Electric Company is to be commended for its initiative in being the first to place breakers of this type in regular service on its system, thus providing the initial service experience.

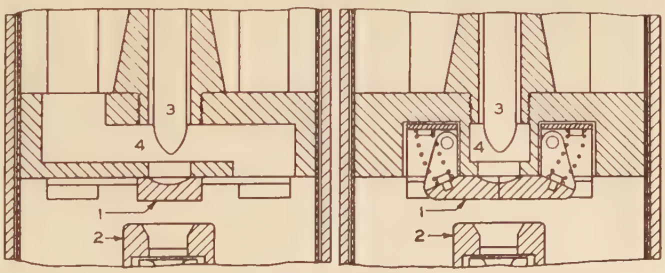
Principles of Operation

Early tests were therefore made on this type of breaker, supplied with cross-blast baffles of substantially the same construction as that used with oil. These baffles have been previously described in the literature, but a brief explanation of their action will be repeated here. Figure 1*a* shows schematically two cross-sectional views, taken at right angles, of a part of a pot using one of these baffles as applied in the oil circuit breaker and with the contacts in the closed position. The interrupting process is started by raising of the contact rod (3). This draws an arc initially from the bottom of the contact rod to the arcing bell (2). As the rod continues to rise and is withdrawn into the central hole of the baffle (figure 1*b*) the metal gates (1) at the lower end of this hole close under the influence of their compression springs, blocking off any direct flow of liquid or gas up through this hole and dividing the arc into two portions in series, one below the baffle and one in its central hole. The arc below the baffle generates pressure which forces the liquid through the cross-blast passage (4), which is shown in figure 1*b*, as entering the baffle from the bottom at the right, then passing horizontally over to the left side of the baffle and finally leaving the baffle from the top on this side. The horizontal passage intersects the central hole of the baffle, so that the liquid forced through this passage by the pressure below the baffle crosses the path of the arc. In oil this had been found to be a very effective means of arc extinction.

Tests on such an arrangement with water as the interrupting medium indicated the scheme to be fundamentally sound, but brought out the fact that the pressure generated by a light-current arc of given length is considerably less in water than in oil, while at high currents the pressures in the two liquids tend to be of about the same magnitude. Thus with an arc of fixed length, the pressure was either too low to supply the necessary cross-blast velocity for interruption at light currents or excessive from the standpoint of material stress at



(a) CLOSED POSITION



(b) INTERRUPTING POSITION

Figure 1. Type H oil-circuit-breaker cross-blast baffle and associated parts in cross section

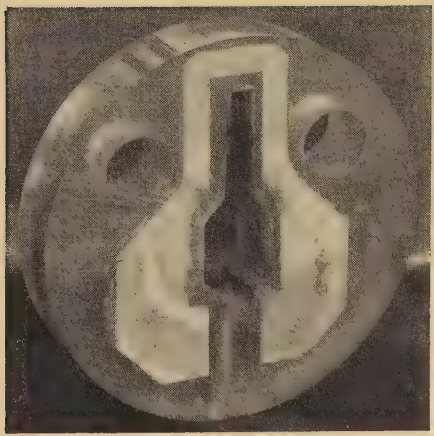


Figure 2. Arc-control baffle

high currents. What was needed was a long pressure-generating arc at low currents and a short one at high currents.

This combination has been obtained without the addition of any moving parts by means of the arc-control baffle shown in figure 2. This baffle consists of a laminated iron core embedded in a disk of insulating material, which is shown as transparent in the photograph, but which is actually a hard rubber material that has been found suitable. It is located between the stationary contact and the cross-blast baffle in such a way that the arc is drawn through the central hole. Its action utilizes a modification of the well-known principle that an arc drawn in a slot of magnetic material is drawn magnetically toward the bottom of the slot. Now fundamentally, the "bottom" of the slot is that end at which the flux in question encounters the lower magnetic reluctance drop. Since iron has a saturating magnetic characteristic, it is obvious that a double-ended slot may be arranged as in figure 2, one end of which has a complete iron path of small section and therefore comparatively low reluctance at light currents and high reluctance at heavy currents, while the other end has an iron path of large section, but with a gap in it, so as to have a reluctance substantially independent of current magnitude. In this slot, light-current arcs are drawn to the end having the complete iron path, while heavy-current arcs are drawn to the end having the larger section.

This results in an arrangement whereby shortly after being drawn light-current arcs will tend to assume one path and heavy-current arcs a different path. If, then, the one path is made long and the other short, as indicated in figure 3, the object is achieved of providing a long pressure-generating arc for light currents and a short one for heavy currents. The pressure generated by this is now sufficient to bring about interruption at all values of current and excessive at none within a rating of 500,000 kva, which is equal to that of the corresponding oil circuit breakers. This results in a satisfactory interrupting performance throughout this

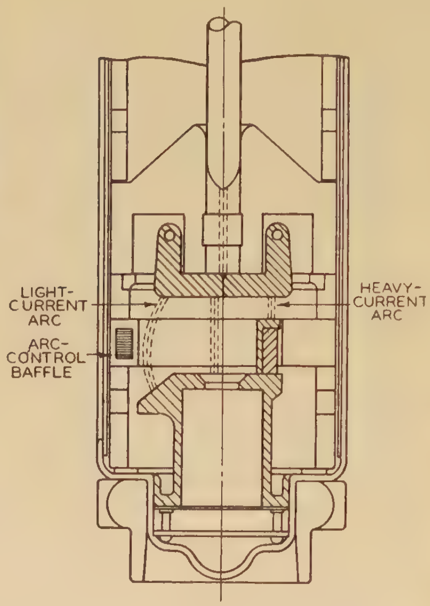


Figure 3. Diagram showing arc-control action

range. Figure 4 shows a photograph of a cutaway section of the interrupting element showing the actual configuration.

In order to remove all dielectric stress from the interior of the pot when the breaker is standing in the open position, a set of external disconnecting contacts has been provided as shown by figure 5 and figure 6. A wood crosshead is used which supports two segment-type contacts at each end. These segment-type contacts co-operate with bayonets which are mounted on cap insulators on top of the pots so as to make contact when the breaker is in the closed position and throughout the major part of the 20-inch stroke, but to leave a gap of about $2^1/_2$ inches above each pot when the breaker is in the open position. The path of current through the interrupting contacts of the breaker then runs from the bottom of one tank up through the contact rod to the two segment contacts which are connected in parallel at one end of the crosshead, thence to the bayonets mounted on the cap insulators, down these and across on the copper tie rods to the top of the cap insulators on the other pot of the same phase, then by a path similar to that followed on the first pot but reversed, to the bottom of this pot. The primary contacts make direct contact from pot to pot, shorting out the bayonets above the pots as well as the internal contacts.

The primary current-carrying contacts of the breaker are of the high-pressure line-contact type which combines the advantages of simplicity, effectiveness, and lightness of moving parts. The 600- and 1,200-ampere breakers use the butt type of contact in figure 5. The ratings of 2,000 amperes and above use double-finger wipe contacts which are also very compact as indicated by figure 7.

Adaptation to Field Service

The use of the arc-control baffle and series air disconnecting contacts de-

Figure 4. Cutaway section of interrupting element

scribed above resulted in the evolution of a hydro-blast breaker capable of supporting a 500,000-kva interrupting rating which is the same as that of the corresponding oil circuit breaker. With the use of the primary contacts, the current-carrying capacity is likewise brought into line. These changes had been made without increasing the space requirements of the breaker and in such a way as to permit modernization of the standard oil breaker in its original cell.

From the point of view of adapting the breaker to the reliable service expected in field operation, the problems involved were mainly those of choice of material. It was obvious from the beginning that exclusive of the new features which made successful the utilization of water as an

interrupting medium, a number of changes would have to be introduced to cope with the altered chemical and physical picture presented inside the interrupting units. The comparable oil breaker had shown itself to be more than satisfactory over a period of many years' service as evidenced by the fact that over 30,000 of these breakers had been put into service throughout this period and operated successfully from the standpoint of both undiminished interrupting ability and unimpaired current-carrying qualities over long periods with very moderate maintenance. The goal set was a breaker using water as an interrupting medium that should be comparable not only in interrupting ability, weight, and cost, but also in sturdy and enduring construction to its proved counterpart in oil.

As a direct outgrowth of the type *H* oil circuit breaker, this breaker assembly includes a number of elements which have undergone only the changes necessary to accommodate them to immersion in water. The Herkolite and fiber parts as well as the plywood baffles and certain steel parts were immediately eliminated

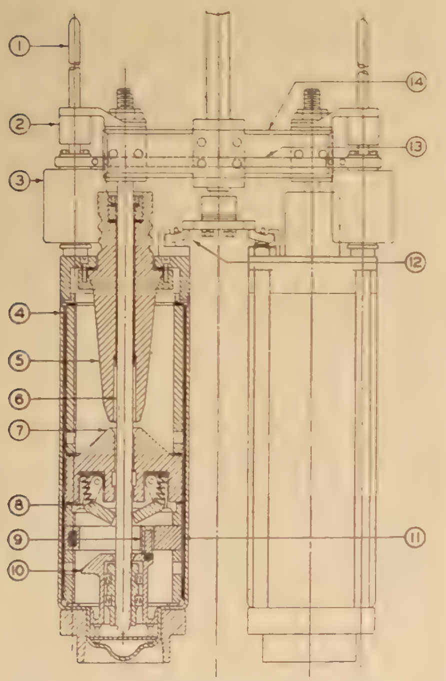


Figure 5. Hydro-blast circuit breaker, 500,000-kva rating

1—Bayonet
2—Segment-type contact
3—Cap insulator
4—Tank lining
5—Bushing insulator
6—Contact rod
7—Cross-blast baffle
8—Gates
9—High-current runner
10—Low-current runner
11—Arc-control baffle
12—Primary contacts
13—Copper tie rods
14—Wood crosshead

because of their deterioration when immersed in water. In their place, a synthetic material was found to be practical for the cylindrical spacers which hold the baffles in their proper locations; the bushing and the arc control baffle are molded of a hard substance which has shown the combination of long life and good mechanical and electrical properties, including ability to withstand the erosive effect of an arc; the tank lining is made of a material which adapts itself readily to the inside of the tank; the cross-blast baffle uses material which has ability to stand up under water and has shown itself to have excellent resistance to the arc. The metals to be used were chosen as a result of extensive steam and weathering tests on various combinations to determine which of them would produce a minimum of corrosion. This resulted in an assortment of metallic materials, including bronze, Elkonite, brass, stainless steel, and tin-dipped steel tank, that showed only slight tarnishing after prolonged exposure.

Water differs from oil in that its breakdown under the influence of the arc is a completely reversible process, leaving no permanent gases. This gave rise to the thought that a vent might be found unnecessary on these breakers and circuit interruption tests without a vent have shown this to be a fact. Thus the separating chambers and vent piping which are conventional on oil circuit breakers are entirely dispensed with.

With the elimination of the vent, the pot becomes practically a sealed chamber and the loss of water by evaporation may be expected to be very slight. Laboratory tests have shown this to be the case. In these tests, a tank was subjected to a

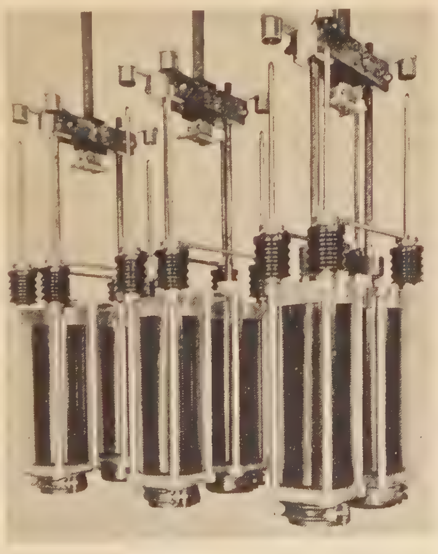


Figure 6. Hydro-blast circuit breaker, 500,000-kva rating, in open position

Table I. Representative Arc Durations at Different Water Levels, 500,000-Kva Hydro-Blast Breaker

Single-Phase Tests at 14,500 Volts, 60 Cycles. Water Level Range—Three Inches

Maximum Water Level		Minimum Water Level	
Current (Amperes)	Arc Duration (Cycles)	Current (Amperes)	Arc Duration (Cycles)
1,200	2.1	1,200	1.5
2,100	1.2	2,900	1.1
4,300	1.5	4,000	1.3
6,200	1.3	6,900	1.3
9,900	1.6	10,000	1.1
12,900	1.4	13,000	1.3
14,300	1.3	20,000	1.2
17,800	1.1	20,500	1.2
19,600	1.3	21,000	1.0
20,000	1.0	24,000	1.0
26,000	1.3		

heating cycle of 12 hours on and 12 hours off, resulting in temperature fluctuations from about 20 degrees centigrade to about 70 degrees centigrade. Under these severe conditions the loss by evaporation was at the rate of about $1^1/_2$ inches per year. Field experience, as might be expected, has shown an even lower loss. The circuit interruption tests listed in table I demonstrate that a water level variation of 3 inches may be allowed without any effect upon the breaker performance, so that a very reasonable maintenance schedule will be satisfactory from this standpoint.

Tests

The breaker has, of course, been subjected to exhaustive tests. Table I,

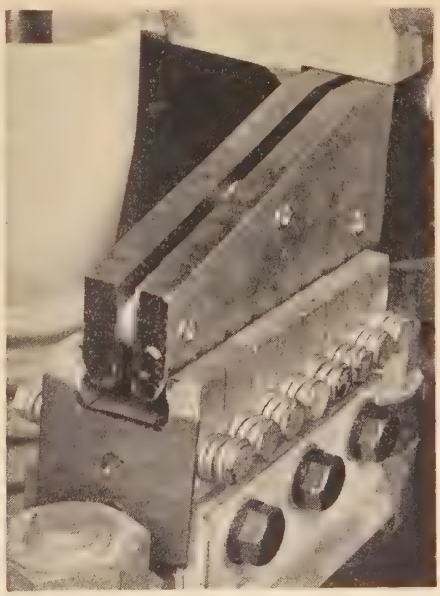


Figure 7. Double-finger wipe contacts

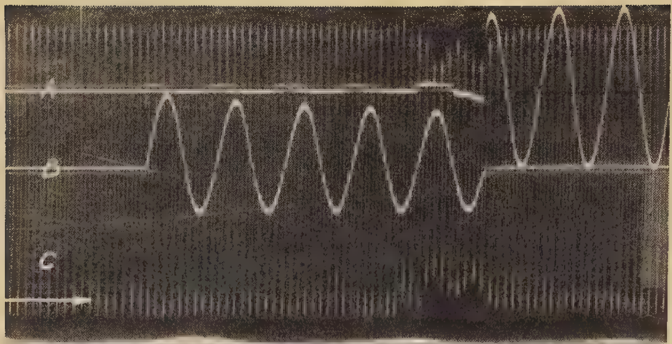
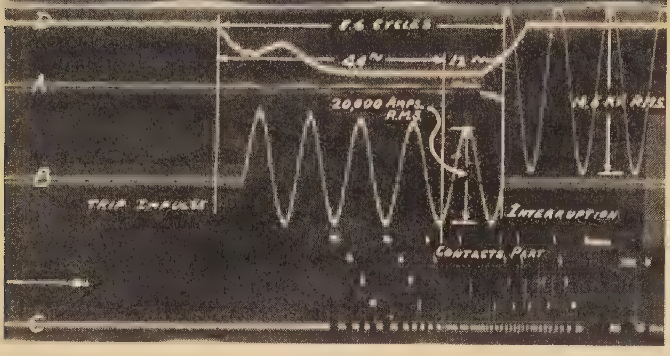


Figure 8. Typical interruption at breaker rating

A—Arc voltage
B—Current
C—Pressure below baffle



A—Arc voltage
B—Current
C—Contact travel—one-half inch per step
D—Trip-coil current

which has already been referred to, shows excellent performance on single-phase tests under the severe conditions of 14,500 volts impressed across a single pole. Table II shows similar data from three-phase tests. Both of these tables show interruption of currents exceeding that corresponding to the 500,000-kva rating of the breaker. Figure 8 shows an oscillogram of a typical interruption approximately at the breaker rating. The arc duration was limited to 1.2 cycles and the over-all time from trip impulse to interruption was 5.6 cycles. The performance is thus substantially the same as that of the corresponding oil circuit breaker.

Field Experience

Six oil circuit breakers which had been in service for some years have been changed over to hydro-blast breakers of the 500,000-kva rating and been in service in this form since the early fall of 1938. During this time as many as three short circuits have been interrupted by a single breaker. All short circuits have been interrupted promptly and expeditiously and the performance has been satisfactory in all respects, the only damage being a very slight burning of the contacts, which is to be expected.

Higher Interrupting Ratings

This paper has been primarily concerned with the 500,000-kva rating of the hydro-blast breaker, which has advanced somewhat farther than the other ratings. Work has progressed far with the development of both the 1,000,000-kva and the 1,500,000-kva ratings, however. Satisfactory circuit interruption tests have been made on a development sample of the 1,500,000-kva rating at current values extending up to 60,000 amperes.

Conclusions

The hydro-blast breaker, using a noninflammable interrupting medium, has been developed in ratings from 500,000 kva to 1,500,000 kva at 15,000 volts. This breaker may be regarded as the latest stage in the development of a circuit breaker which has enjoyed continuous high popularity, as the incorporation of one improvement after another has kept it well abreast of the art. The hydro-blast breaker has the same overall dimensions as the oil circuit breaker of which it is an outgrowth, substantially the same general arrangement, and the same performance characteristics, except that the presence of inflammable liquid has been entirely eliminated. The various interrupting problems introduced by the change from oil to water have been overcome, and six months' field experience has confirmed the practicability of the arrangement.

Table II. Representative Arc Durations, 500,000-Kva Hydro-Blast Breaker

Three-Phase Tests at 14,500 Volts, 60 Cycles

Current (Amperes)	Arc Duration (Cycles)	Current (Amperes)	Arc Duration (Cycles)
1,180	1.7	16,000	1.4
1,320	1.9	15,000	1.5
1,320	1.9	17,000	1.5
4,500	1.7	18,000	1.4
4,000	1.6	16,000	1.6
4,800	1.7	15,800	1.6
6,800	1.7	23,000	1.7
6,600	1.9	22,000	1.8
7,100	1.9	22,000	1.8
9,500	1.5	27,000	1.7
9,500	1.7	30,000	1.4
10,300	1.7	20,000	1.7

Discussion

J. A. Elzi (The Commonwealth & Southern Corporation, Jackson, Mich.): Developments in circuit breakers utilizing noninflammable material in place of oil as the arc-extinguishing medium are of considerable importance and the results obtainable by using water for this purpose, as described in this paper, are highly interesting. The oscillograms and test results given seem to indicate that in general the performance of this breaker is quite comparable to that of an oil circuit breaker.

As the authors have mentioned, water is readily available, but presumably the water used in the breaker would have to meet certain requirements as to purity to avoid corrosion within the breaker and to maintain its arc-interrupting ability. It would seem that even a very small percentage of impurity in the water might be detrimental and since it would, no doubt, be necessary to inspect the contacts after the breaker has operated at near its rating, the question arises as to what precautions would be necessary when such an inspection is made.

It also seems that every precaution would need to be exercised to avoid ever having the water freeze in the breaker. In case this were permitted to happen, the breaker would not only be inoperative during the time the water was frozen, but it would seem logical to expect such freezing to result in permanent damage to some of the internal parts of the breaker. It would be interesting to know if any antifreezing solutions are available which would be satisfactory.

The breaker tanks are not provided with any vents and it would appear that excessive pressures might be built up if a breaker of this type were applied on reclosing service and that the derating factors for this type of service would of necessity be quite a bit more severe than those now applicable to modern oil circuit breakers.

A. C. Schwager (Pacific Electric Manufacturing Corporation, San Francisco, Calif.): The authors have to be commended for the ease with which they have been able to transform one of the most popular oil circuit breakers into one in which the hazard of an inflammable liquid is eliminated.

On a recent study trip in Europe, I had the opportunity of examining various water circuit breakers, but in spite of the several years of development, breakers of 1,500,000 kva, as described by the authors, were not available. In Europe the water circuit breaker has not been entirely satisfactory and just recently its manufacture has been

abandoned by at least two large manufacturers. In some breakers installed it was found advisable to change the interrupting liquid back to oil, in order to obtain more satisfactory operation. In view of these facts, one can more fully appreciate the difficulties which the authors have had to overcome in developing the breaker described.

In connection with the design proper I would like to ask a few questions:

(1). In closing in slowly on a short circuit, an arc is formed and steam is generated prior to the time the contacts touch. This high-pressure steam can exert a considerable force upon the moving contact, retard and possibly prevent the closing. I wonder if this phenomenon has been observed, and if so how its effect was overcome.

(2). Although water eliminates the danger of fire hazards, European practice, using Herkolite and fiber parts within the chamber, has shown that a sustained arc can produce a sufficient amount of gas completely to smoke out a station. It would be interesting to know if this shortcoming has been eliminated in the materials developed by the authors, particularly if the gases are of nonpoisonous nature.

(3). I am sure that this new development has thrown considerable light upon the theoretically involved problem of arc interruption. The authors refer to the high dielectric short-time strength of water; the question therefore arises whether this factor alone is sufficient to explain the performance. Several cycles elapse from the time the arc is interrupted to the instant the series air gaps open. Is the insulating ability of the breaker during this relatively long time interval due to a layer of water interposed between the contacts or due to the presence of steam?

B. P. Baker (Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): The reaction to the unique development described in the paper by Messrs. Skeats and Saylor will be most interesting to those concerned with the trend in American switchgear development.

I concur with these gentlemen in their belief that "the oil circuit breaker has for many years given a very good account of itself in the United States."

For some years we have recognized that there are rather special applications where the duty and frequency of operation are extremely severe. In these cases the complete elimination of oil, accessibility of contacts, and reduced maintenance requirements have justified our offering a line of oilless circuit breakers up to approximately 800,000 kva at 15 kv.

As early as 1922 we became interested in water as an interrupting medium, and even went so far as to acquire rights under the Nicholson patents. For a good many years now we have watched the work of a large European company on the "expansion" breaker, which was the first commercial form of water breaker. We have bought and tested various types of these breakers for both high and low voltages, and have obtained considerable information about their performance. Up to the present time however, our conclusion has been that the water breaker is not as well suited to American requirements as the De-ion type of air breaker.

We note that Messrs. Skeats and Saylor have carried their interrupting tests on a development sample of the 1,500,000-kva rating to 60,000 amperes. In view of the rather high power represented by such laboratory tests, it would be interesting to know at what voltage they were made and whether any special test connections were used.

The authors seemed to have investigated thoroughly the suitability of materials for operation in water and have reported on their adaptability from the corrosion point of view. Their conclusions generally confirm the results obtained by us. While the effect of the water on certain materials may not be serious, I do not believe that we can safely conclude that the effect of the various materials on the water can be taken too lightly. It would, therefore, be of interest to know the kind of water used, the upper limit of conductivity, and how this is affected by time and interrupting duty.

In this interrupter the old problem of volts interrupted per inch of arc as an inverse function of current reappears. Here again a rather ingenious solution has been offered by moving the arc from its point of inception, in one direction to lengthen it for low currents and in the opposite direction to shorten it for high currents. It seems rather unfortunate that at high current it is necessary to draw a long arc and then deliberately move it from its point of inception in order to shorten it, thus consuming unnecessary time, producing extra burning, arc energy, and pressure.

The author points out that in contrast to an oil breaker the water-breaker "pot becomes practically a sealed chamber", and at another place "pressure generated by a light-current arc of given length is considerably less in water than in oil, while at high currents the pressures in the two liquids tend to be of about the same magnitude". How these two conditions can exist needs explanation. Our experience indicates that the total volumes of gas generated are approximately the same for oil and for water but that a larger part of the gases formed by the arc in water rapidly recombine or condense leaving a smaller volume of permanent gases. At high currents the rate of generation is so high that condensation during that time is almost negligible and the pressures produced are about the same as for oil. However, at low currents the condensation of the steam is not negligible and the pressures generated are less than those when oil is used. This relatively faster condensation may be caused not only by the smaller rate of gas generation but also by the smaller bubbles which have walls closer to the arc and which have a relatively larger surface area in proportion to the volume of the bubble.

I was surprised to find that the average speed of the contacts from the point of separation to arc extinction is approximately 25 feet per second and I am wondering if I have interpreted the oscillogram correctly. With two series breaks per pole the arc is lengthened at the rate of approximately 50 feet per second. I had never regarded the *H* breaker as having such tremendous acceleration and wonder if there is anything inherent in this type of water breaker which requires such speed. Since the moving parts include the main contacts as well as the auxiliaries, I would be interested in knowing what special means have been required to get the acceleration and shock-absorbing effect.

D. C. Prince (General Electric Company, Philadelphia, Pa.): For many years there has been a search for some liquid which could be used in place of oil in a circuit breaker. The ideal liquid would possess such properties of transil oil as dielectric strength, especially under arcing, and, at the same time, be noninflammable. It should, of course, have other properties, such as constant viscosity, stability, low volatility, be noncorrosive, and have low cost, to mention only a few of the requirements.

For several years we have made a practice of trying out as a circuit-breaker fluid any liquid that anybody cared to mention, which offered any hope of success. Of all the liquids tried, water alone has seemed to offer any possibility of being useful in a commercial design.

Now that a water breaker has been produced which meets the exacting requirements of the high-power test station, and which makes possible an oilless circuit breaker up to the highest commercial ratings for station service, the next step is to see how such a design will meet the requirements of day-to-day operation in the field.

W. F. Skeats and **W. R. Saylor**: Mr. Elzi and Mr. Baker have asked about the purity and other characteristics of the water. The water used in the majority of tests on the hydro-blast breaker is Schenectady tap water. A typical series of about ten interruptions at moderate and high currents has been shown to reduce the resistivity of this water about 50 per cent with no accompanying deterioration in performance of the breaker. Inasmuch as the resistivity of the water has been quite low in all tests, it seems obvious that the presence of minute amounts of impurities such as might be picked up from the metals or insulating parts of the breaker would have no deleterious effect, and the successful field experience, of almost a year, as well as the many interrupting-capacity tests seems to bear this out. In view of the wide variations in tap water throughout the country, however, distilled water is recommended for general use.

It is not necessary to inspect the contacts of the water circuit breaker any more frequently than those of the corresponding oil circuit breaker, and the necessary precautions at the time of inspection are no more stringent than in the case of the oil circuit breaker.

Since these are indoor breakers, it is not felt that the requirement that the water should not freeze is at all embarrassing. However, antifreeze has been in use in this connection in Germany for a number of years.

The pressures obtained in the air space of the breaker are but a small fraction of those below the baffle and of that which the structure will stand, so that the absence of vents will not affect the derating factor on reclosing service.

The problem of circuit closing has been

met by a modification of the disconnecting contacts causing them to close after the interrupting contacts, and an arrangement has been developed which has been found satisfactory at the highest currents.

In order to determine the nature and extent of disturbance upon failure, this breaker has been opened under a short circuit of rated interrupting capacity without water in the tanks. After a few cycles of arcing inside the tanks, the arc was transferred outside the tanks, generating no more smoke than any other arc in air. Furthermore, with the cubicle arrangement now used with these breakers, such smoke as is generated should be largely confined to its own cell. The gases are not poisonous.

Unfortunately the development throws no light on the mechanism of arc interruption in the way that Mr. Schwager anticipates. The disagreement in this field centers upon the first millisecond or less after current cessation. Beyond this time there will be little disagreement that there will be sufficient dielectric between the contacts of such a breaker as this to render the voltage gradient across it comparatively low.

With reference to Mr. Baker's question, no special test connections were used, the breaker being tested up to the capacity of the testing plant at 14,500 volts, 8,400 volts, and 4,200 volts. The 60,000-ampere tests were obtained at 4,200 volts across a single-pole unit, but with only one breaker tank per pole instead of two. With this breaker these should be the equivalent of tests at about 8,000 volts, which is very nearly equal to leg voltage at 15 kv.

It is considered very unlikely that a long arc ever exists at the pressure-generating gap under high-current conditions. The metal piece which forms the lower terminal of the high-current arc as shown in figure 3 of the paper is fairly close to the contact rod when the latter extends through the arc-control baffle, and with the normal rapid expansion of the high-current gas bubble and the magnetic effect of the arc-control baffle combined, it is believed that the arc will strike from the contact rod to this metal piece while their separation is still quite short.

The explanation which Mr. Baker offers for the difference of the pressure characteristic of water from that of oil is very interesting and parallels closely one which has been suggested by the authors' associates. Another contributing factor may lie in the fact that oil is a mixture while water is substantially a single substance. Thus the more volatile constituents of the oil in the neighborhood of the arc may be vaporized rather readily by a light current, so that more gas in proportion would be generated in oil by a light current than by a heavy current. Since no such effect occurs in the case of water, a difference in the pressure characteristics similar to that which has been observed may be expected.

This breaker uses no special means for acceleration and shock absorption other than those standard on the *H* circuit breaker.

The question of the future of this type of breaker is one which only time can answer. The authors have been aware, of course, of the recent European history of this type of breaker and have had available complete design data on the water breakers manufactured by one of the European companies. They have made tests embodying these ideas and, as Mr. Baker has done, found them not very well suited to American practice. They believe, however, on the basis of both laboratory tests and field experience that the present breaker has overcome all serious shortcomings. Therefore, since this breaker exceeds by almost two to one the interrupting capacity of any earlier oilless breaker in its voltage range, it seems to be indicated that until other oilless breakers show a much greater advance than in the past few years, the hydro-blast circuit breaker will enjoy a good field of application.

The Anomalous Behavior of the Moving Systems of Single-Phase A-C Watt-Hour Meters at No Load

F. C. HOLTZ
MEMBER AIEE

Synopsis: Investigation reveals the moving systems of induction watt-hour meters to be in a peculiar state of motion under the condition of potential excitation only. The present paper offers a simple explanation for its origin and provides a method for recording and determining the actual value of the motion in various parts of the moving system. Interesting conclusions may be drawn from the investigation which throw much light on the problem of meter-bearing performance.

IT IS generally known among electric metermen that the moving systems of a-c watt-hour meters under the condition of no load with potential element excited are in a peculiar state of vibration. This phenomenon frequently exhibits itself as a rattle or vibration of the upper pivot if unoiled and is easily felt by slightly touching the edge of the disk with one's finger.

The writer, when discussing this matter with George F. Shotter of London, England, was advised that under suitable illumination and with sufficient magnification the actual motion of the peripheral edge of the disk had been observed as a figure eight, characteristic of Lissajous' curves. This discussion led the writer to investigate the phenomenon and develop methods for more accurately observing and recording the motion. Such motion can also be predicated on theoretical grounds as illustrated by the following considerations which are sufficiently accurate to explain the observations and predict the general nature of the motion. The total labor may be considerably reduced by making some very obvious assumptions as follows:

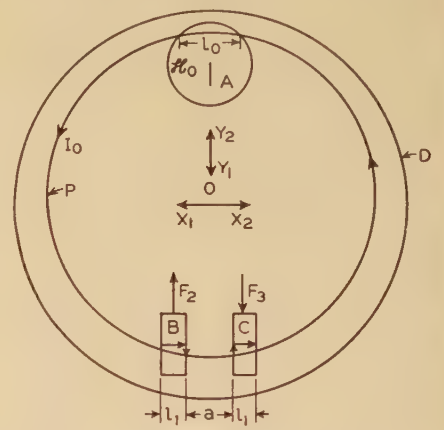


Figure 1. Elementary diagram of disk and interacting elements

1. The distribution of the driving and damping fluxes associated with the meter disk are generally symmetrical with respect to a plane perpendicular to and passing through its center.

2. The movement being very small and the upper pivot being at a considerable distance from the disk, it is assumed that the motion is parallel to the plane of the disk and that the motion of the lower pivot is substantially that of the center of the disk.

3. The total eddy-current distribution in the disk which causes the motion may be replaced by an "equivalent" filament of current interacting with the field of the permanent magnets and the a-c potential-element field.

4. The impedance of the path through

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which the filament of eddy current circulates is wholly resistance.

5. The permanent-magnet damping fields are of equal but opposite strength and symmetrically placed with respect to the plane referred to above.

With these assumptions we may proceed with the equations of motion in the steady state in which,

$\mathcal{H}_0$ = maximum value of the assumed uniformly distributed field strength as shown in figure 1
f = frequency
$\omega = 2\pi f$
I_0 = maximum value of the "equivalent" eddy current in the disk
l_0 = length of the eddy-current path in the a-c field
l_1 = length of the eddy-current path under each of the permanent magnets
H = intensity of the permanent-magnet field in the disk at the points associated with the eddy current
$\mathcal{H} = H_0 \sin \omega t$ = instantaneous value of the a-c field strength. If i is the instantaneous value of the eddy current in the disk we have, in view of (4)
$i = I_0 \cos \omega t$

Referring now to figure 1, let P denote the filament or equivalent eddy current

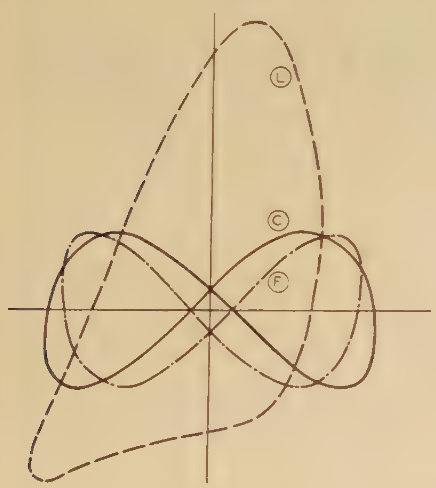

Figure 2. Motions derived from simple theory

in the meter disk, D and A, B and C, the respective locations of the a-c and d-c fields.

The force caused by the interaction of the a-c field and the equivalent eddy-current filament is

$$F_1 = l_0\mathcal{H}_1 = \mathcal{H}_0 l_0 I_0 \sin \omega t \cdot \cos \omega t = K \sin 2\omega t$$

where K is a constant. It is therefore seen to be a double-frequency quantity and with the usual assumptions as to symmetry and direction of field is directed through the center of the disk along the line Y_1Y_2.

We may also assume that this produces a harmonic motion of the disk in the same direction but in view of its inertia, and other factors, the motion is not quite in phase with the force but differs therefrom by a small angle α.

With these assumptions the component of motion of the center of the disk arising from the interaction of the eddy currents and a-c field is of the form $y = K_1 \sin (2\omega t + \alpha)$. The disk, as a whole, will also be moving in the same manner.

The same eddy current will also interact with the field of the permanent magnets B and C. The filament of eddy current under each magnet may be resolved into two components which are parallel and perpendicular respectively to the direction Y_1Y_2. As may be seen in the figure, the components parallel to the Y_1Y_2 direction are relatively small and may therefore be ignored in the present analysis. It is interesting, however, to observe that since these components in respect to each magnet are relatively reversed and the magnetic field is also reversed the effect is to produce an oscillation of the disk about its center. The components of the eddy current under the magnets and perpendicular to the line Y_1Y_2 interact with the field, H, to produce forces in the disk parallel to this direction.

Under the magnet B there exists a force

$$F_2 = Hl_1I_0 \cos \omega t$$

And under C a force

$$F_3 = -Hl_1I_0 \cos \omega t$$

It is apparent that these two forces combine as a couple of moment

$$M = F_2(a+l_1) = (a+l_1) \cdot Hl_1I_0 \cos \omega t$$

Since the observed motions are of extremely small magnitude we may assume that this moment gives rise to a component of motion of the center of the disk along the direction X_1X_2 of magnitude

$$X = K_2 \cos (\omega t + \alpha_2)$$

Where K_2 is a constant for any given set of conditions.

It is to be noted that this motion is harmonic and of the same frequency as the supply. By suitably readjusting the value of α, we may rewrite the equation of motion of the center of the disk in parametric form.

$$y = K_1 \cos (2\omega t + \alpha_1)$$

$$x = K_2 \cos (\omega t + \alpha_2)$$

Since y goes through its period twice as fast as x the curve in general consists of two loops. These curves are, in fact, the typical Lissajous' curves.

In view of the numerous factors which present themselves in attempting a general solution of the disk motion, it cannot be argued that the simple equations above adequately represent all actual possible motions of the system. Some difficulty would, for example, be encountered in even the more simple case of evaluating the inertia, damping coefficients, and other restraining forces under the action of the single force in order to arrive at the equations of motion. They do, however, give a very close approximation by assigning various constants in the equations of motion.

In precisely the same way it is possible to establish the corresponding motion of other portions of the disk. This has been done and by appropriate choice of constants, and transformation equations the relative motions have been plotted in figure 2 in which C represents the motion of the center of the disk; L, the left peripheral edge, and F, the front peripheral edge between the magnets. In this sense the constants were merely varied until the curves corresponded with the observed values rather than using the equations to predict the actual observed motion. It will be seen that these curves do represent with considerable accuracy the nature of the observed motion and therefore the

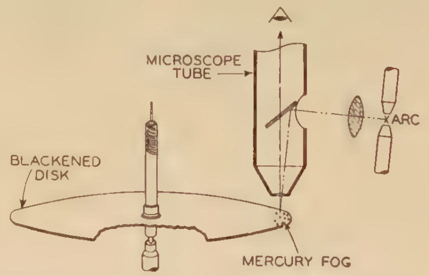

Figure 3. Setup for observing motion at edge of disk

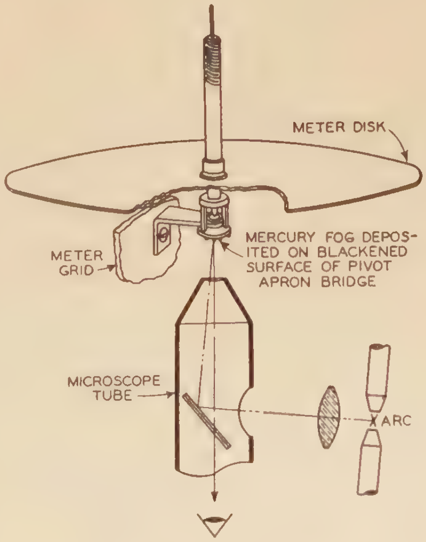

Figure 4. Setup for observing motion at center of disk

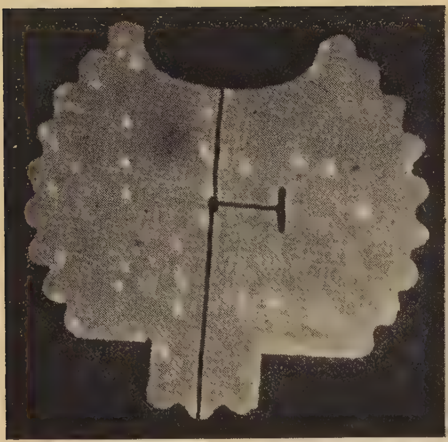

Figure 5. Center of disk, no excitation

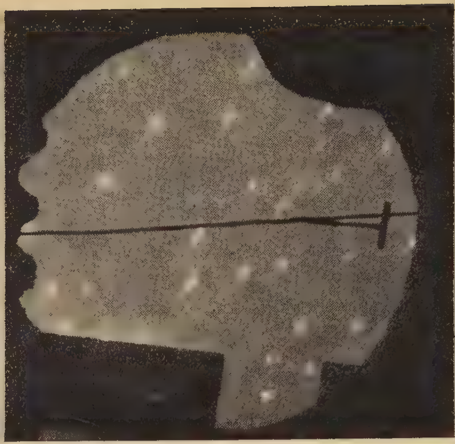

Figure 6. Left edge of disk, no excitation

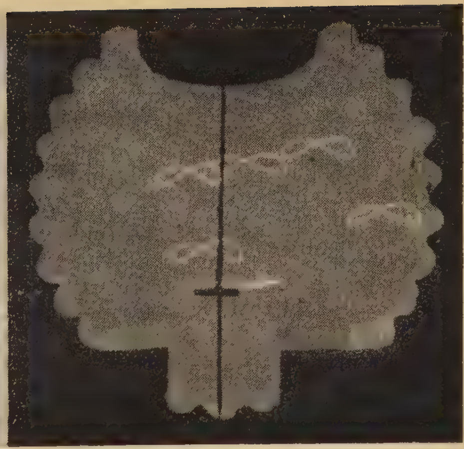

Figure 7. Center of disk, 115 volts, 60 cycles

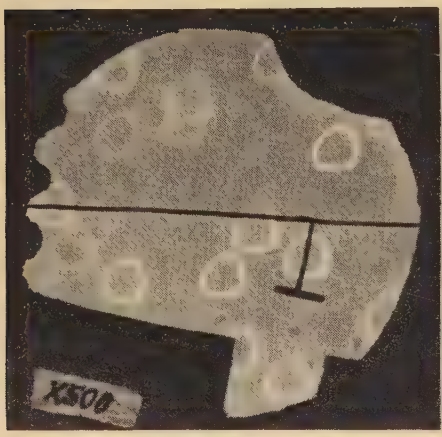

Figure 8. Left edge of disk, 115 volts, 60 cycles

Figure 9. Front edge of disk, 115 volts, 60 cycles

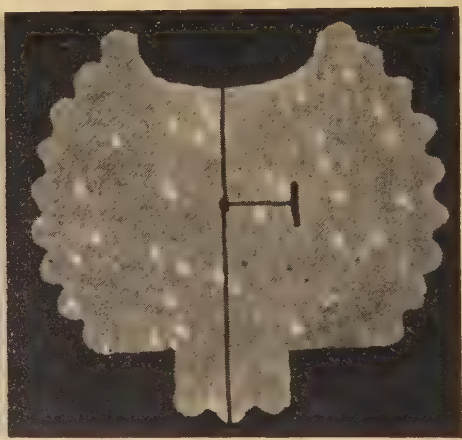

Figure 10. Center of disk, 90 volts, 60 cycles

simple assumptions are sufficient to predict its origin.

Experimental Procedure

Since the magnitude of motion was extremely small and the observations had to be made without interfering with the general arrangement of meter parts, a photographic record of the motion was not obtained without some difficulty. A simple and also beautiful procedure was finally arrived at in the following manner.

The disk was first given a heavy coat of lacquer heavily charged with lamp black. This, on drying, gave a surface which produced no reflection and hence appeared uniformly black even under intense illumination. The surface was then momentarily subjected to the action of mercury vapor which collected small globules of the order of 0.0001-inch diameter and smaller. These small globules would remain on the surface undisturbed and when viewed with a microscope of high magnification and intense vertical illumination the appearance was that of a star image of unusual brightness and small size. When the disk was in motion each tiny spot, due to persistence of vision, produced a true figure of the motion which could be measured and photographed. The general arrangement of apparatus is shown in figure 3.

In order to observe and record the motion of the center of the disk, the arrangement shown in figure 4 was used. In this case the jewel screw was replaced by a small bracket secured to the meter grid and on this was mounted the jewel which supported the meter pivot and moving system. By cutting away the dust cap surrounding the pivot until it resembled an inverted U it was possible to bridge this with a small strip on which the mercury globules had been deposited. The microscope in an inverted position gave the desired view.

Figures 5 and 6 are photographs showing the appearance of the illuminated points at the center and left edge respectively for the condition of no current and no potential excitation. In these as well as subsequent photographs the magnification was 500 diameters. Since there was some possibility that the motions might be influenced by the location of the anticreep slots, these were marked on the negative by a short bar connected to the center of the disk. No appreciable influence was however observed.

Figures 7, 8, and 9, show the motion for no current and normal excitation for the center, left edge, and front, respectively. The close similarity between these three photographs and those shown in figure 2 is to be noted, indicating that the simple assumptions made at the beginning are sufficient to account for the observed motion. As is to be expected, a reduction in voltage should give a corresponding reduction in the motion. This is shown in figures 10, 11, and 12, showing the motion at the center, left, and front edge respectively when the voltage is reduced from 120 to 90 volts. On account of the friction offered by the pivot, there is a point where the motion ceases at the center and becomes purely one of rotation. The above figures illustrate this. In a like manner increasing the voltage makes the effect more pronounced as is shown in figure 13, which illustrates the motion of the pivot at 135 volts.

Removing the permanent magnets has the effect of wiping out the single-frequency motion as is shown in figures 14 and 15 representing the condition at 170 volts, 60 cycles. Under these conditions reducing the voltage to 115 volts had the effect of completely arresting the motion as shown in figures 16, 17, and 18, illustrating the center, left, and front edge respectively. This condition is brought about by the fact that the pivot friction was sufficient to prevent motion, yet in the earlier photographs where higher forces caused the pivot to move, the double-frequency forces were able to act while the pivot was in motion.

Removing one of the magnets caused a pronounced change in motion as can be determined from the equations. In this case the motion is almost entirely in a radial direction across the remaining magnet. Figures 19 and 20 show the motion at the center and left edge respectively. Many other interesting effects can be pro-

Figure 11. Left edge of disk, 90 volts, 60 cycles

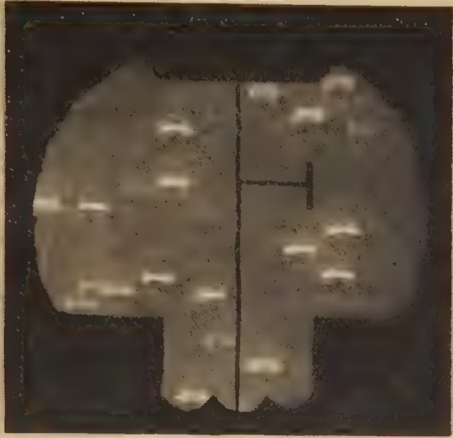

Figure 12. Front edge of disk, 90 volts, 60 cycles

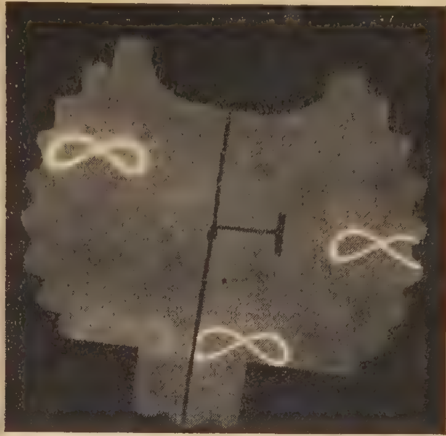

Figure 13. Center of disk, 135 volts, 60 cycles

Figure 14. Front edge of disk, magnets removed; 170 volts, 60 cycles

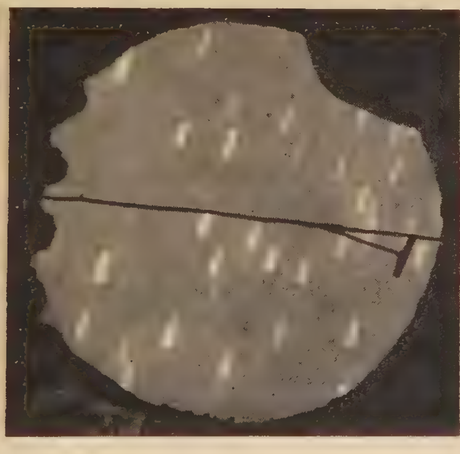

Figure 15. Left edge of disk, damping magnets removed; 170 volts, 60 cycles

Figure 16. Center of disk, damping magnets removed; 115 volts, 60 cycles

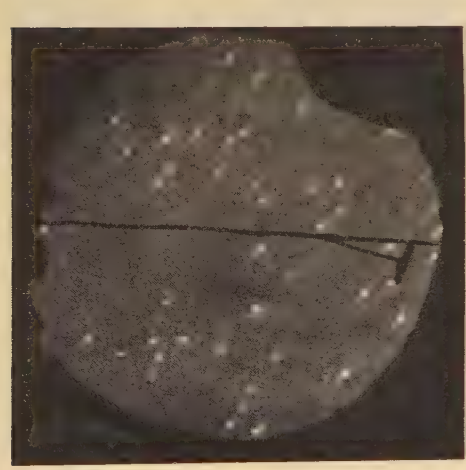

Figure 17. Left edge of disk, damping magnets removed; 115 volts, 60 cycles

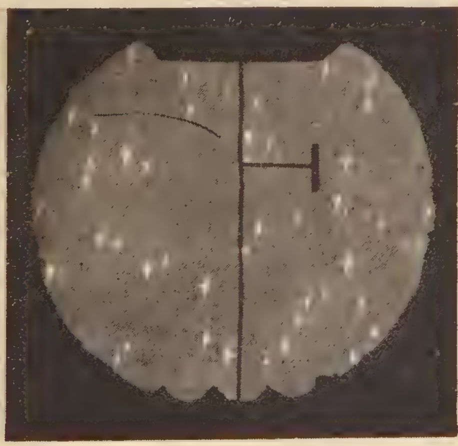

Figure 18. Front edge of disk, damping magnets removed; 115 volts, 60 cycles

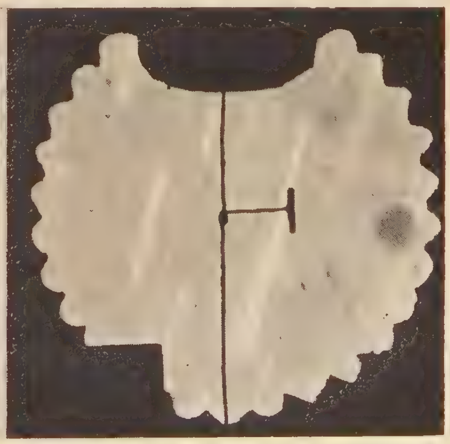

Figure 19. Center of disk, right-hand magnet removed; 115 volts, 60 cycles

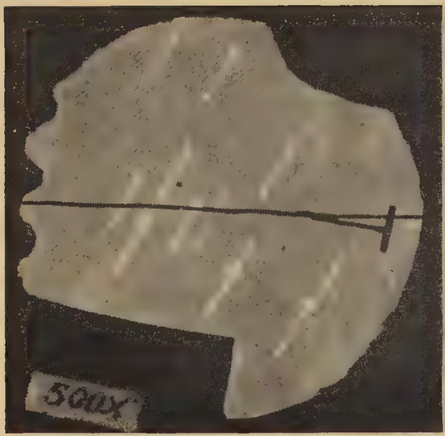

Figure 20. Left edge of disk, right-hand magnet removed; 115 volts, 60 cycles

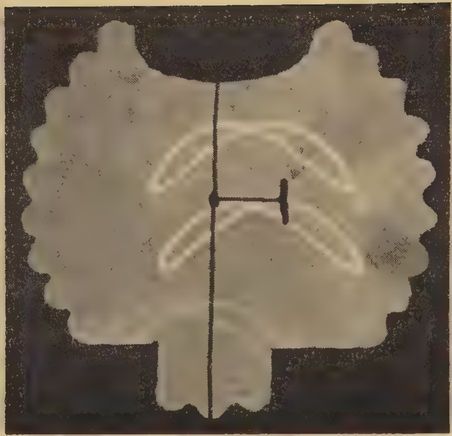

Figure 21. Center of disk, 115 volts, 40 cycles

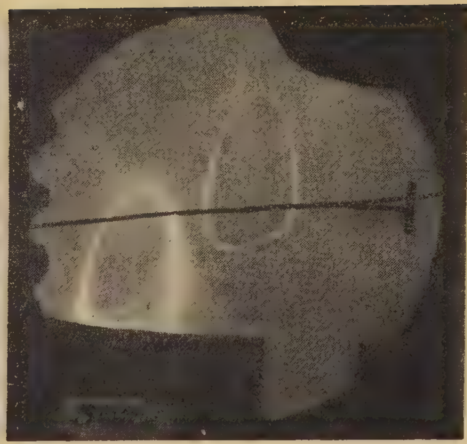

Figure 22. Left edge of disk, 115 volts, 40 cycles

Figure 23. Front edge of disk, 115 volts, 40 cycles

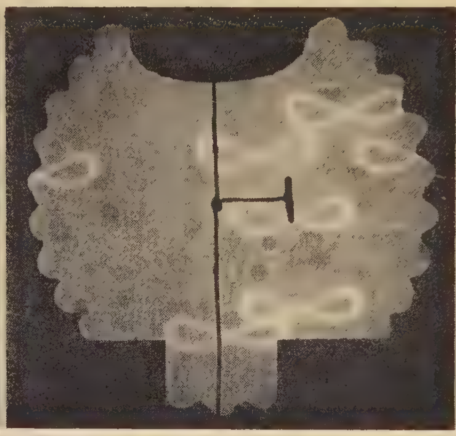

Figure 24. Ball-bearing construction; center of disk, 115 volts, 60 cycles

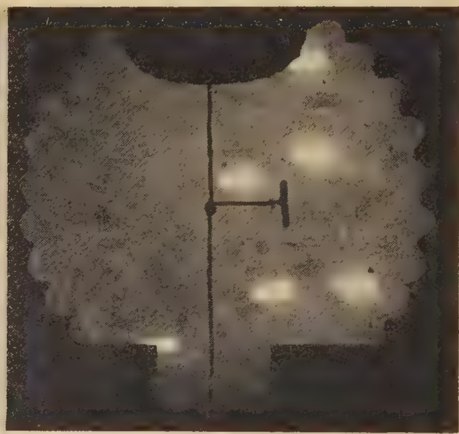

Figure 25. Ball-bearing construction; center of disk, 30 volts, 60 cycles

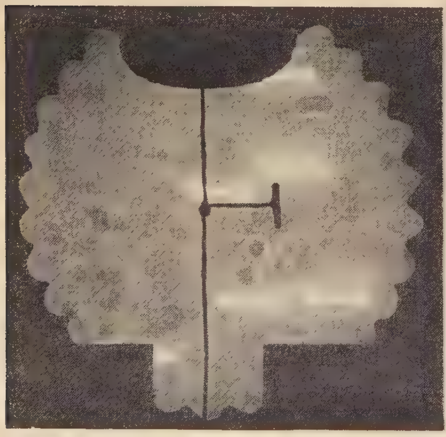

Figure 26. Ball-bearing construction; center of disk, 60 volts, 60 cycles

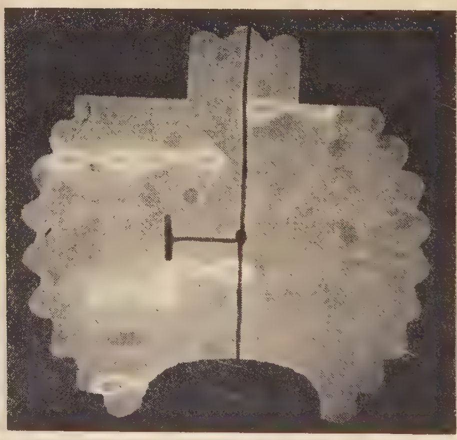

Figure 27. Ball-bearing construction; center of disk, 90 volts, 60 cycles

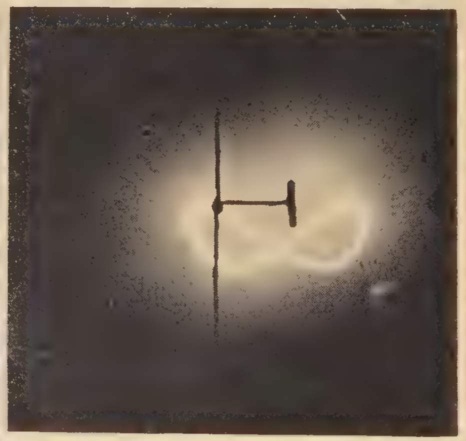

Figure 28. Ball-bearing construction; center of disk, 180 volts, 60 cycles

duced according to the variations made in the factors going into the constants of the equations. A reduction in frequency, for example, greatly amplified the figures as shown in figures 21, 22, and 23 showing the motion of the center, left, and front edge at normal voltage and 40 cycles.

Behavior of Moving System With Ball-Bearing Support

Because of the equally common use of the ball-type bearing, further tests were made to determine the relative motion of the disk under operating conditions similar to those applied to the meters with pivot-type bearing. In this type of bearing a $^1/_{16}$-inch ball moves between two sapphire cup jewels of approximately the same dimensions as those used with the pivot-type bearing. One jewel is carried by the meter spindle while the other is mounted in the lower jewel screw. In

order to draw conclusions as to the relative motion in both types of bearings under the stated condition, several photographs were made at the same voltage and frequency used in previous tests.

Figure 24 shows the motion of the center of the disk at 115 volts, 60 cycles. This should be compared with figure 7 which shows the motion of the center of the disk using a pivot-type bearing under similar conditions. It is to be noted that in this case the extent of oscillation is approximately double, indicating greater freedom of motion but not entirely so. The mechanical characteristics of the system are such as to permit a greater motion under the same forces.

In order to determine if the ball-bearing system exhibited lower friction and was therefore more responsive to the forces, photographs were taken at lower voltages as shown in figures 25, 26, and 27. It is to be noted that even at 30 volts some motion is recorded while at 90 volts it is very considerable. Figure 27 is to be compared with figure 10 which shows no appreciable motion under similar conditions. Figure 28 illustrates the motion at still higher voltages. In order to show the motion resulting from the double-frequency forces of the potential element only, the damping magnets were removed and photographs were taken at 180 volts, 60 cycles. This is clearly shown in figure 29.

It may be said that the motion of the disk when supported by a ball bearing is similar to that which takes place with a pivot bearing but of considerably greater magnitude.

Conclusions

Among the various conclusions to be drawn from the present study are the following:

1. The simple assumptions adequately explain the observed motion.

2. The motion can be reduced by (*a*) not having the electromagnet too near the edge of the disk, and (*b*) keeping the active area of the permanent magnets as near together as possible and of equal strength.

3. The motion of the meter pivot under no-load condition is in the form of a figure eight and the total travel as taken from the curves is approximately 0.002 inch per cycle or 0.12 inch per second. It is interesting to compare this amount of motion with the amount of motion which takes place between the pivot and jewel as a result of full load on the meter.

In this case the pivot moves up the side of the cup jewel until the forces are balanced by an amount such that the point of contact on the surface of the pivot is at a distance approximately

Figure 29. Ball-bearing construction, damping magnets removed; 180 volts, 60 cycles, center of disk

0.005 inch from the central axis.

Using a full-load speed of 0.4 revolutions per second, this results in a motion of 0.012 inch per second which is only of the order of one-tenth that referred to above. Since the pressure between pivot and jewel is approximately the same in both cases it may well be argued that the tendency toward wear of the pivot would be roughly ten times as much at no-load as under full-load operation and that the former takes place over an area of the jewel which is directly conducive to light-load inaccuracies. It must also be remembered that these same forces are active when the meter is under load and may therefore contribute to the wear.

An old assumption not wholly in accord with facts was that the amount of pivot wear was roughly proportional to the total number of meter-disk revolutions. The present investigation as applied to the pivot and cup type of bearing tends to indicate that the amount of wear is dependent upon the total number of hours during which the meter is standing idle with only potential applied, plus some function of the total number of revolutions. This might be expressed in the form of an equation as follows:

$$W = T + R + f(T,R)$$

where

W = wear
T = time in hours
R = total number of revolutions
$f(T,R)$ = some unknown function of both time and revolutions since these effects are not wholly independent

It must, however, be stated that the nature of meter-bearing wear is so complex and subject to so many unknown variables that it is quite unsafe to make any arbitrary assumptions except as we may ascertain new facts which would throw more light on the problem and explain a relatively large mass of observations.

It is, moreover, interesting to study briefly the behavior of the ball-type bearing under similar conditions of no-load operation. Since there exists no appreciable side thrust under the condition of no load, this bearing may be thought of as no more than a ball between two flat horizontal surfaces.

Under these conditions almost perfect rolling motion is secured with the result that there should be little or no wear. Since on appreciable load there is a combination of rolling and sliding, we may, as before, write the equation for wear as follows

$$W = R + f(R,T)$$

to indicate that the wear is almost wholly a function of disk revolutions and time, the latter being necessary to take care of such matters as corrosion, etc. Heretofore it has been the practice to lubricate pivot- and cup-type bearings while the ball bearings are not lubricated, although lately some manufacturers have recommended against oil in either type.

In this respect the conclusions to be drawn from the present investigation points clearly to the fact that without lubrication and under similar conditions any given alloy will perform better in a ball-type bearing than as a pivot type as related to watt-hour meters. This conclusion appears to be completely supported by experimental evidence.

Discussion

Otto A. Knopp (Pacific Gas and Electric Company, Emeryville, Calif.): To anyone interested in research work it is a delight to read the paper presented by F. C. Holtz and especially to people who are interested in watt-hour meters.

Watt-hour meters more or less as we know them today, have been operated for some 40 years with jewel bearings of conventional construction. Still we have learned very little of the behavior of the bearing so as to improve its performance.

Up until 15 years ago the watt-hour meter had many weaknesses and limitations so that the jewel bearing was considered on a par with, or better than, the other parts of the meter. Improvements in the design of the watt-hour meter during the last 15 years have removed many of its weaknesses and limitations, and the jewel bearing now stands out as the weakest member in its structural makeup.

A great many new designs for meter bearings have been proposed and perfected during the past several years, based, however, merely on service experience and limited tests and assumptions. Because of the lack of factual information, it is exceedingly difficult to decide which type of bearing will

be the best from the standpoint of long-life performance and cost.

Research work described in the paper presented by Mr. Holtz throws an entirely new light on the situation by bringing out the fact that the wear of the jewel bearing is greatest during the hours of no load on the meter. Wear on the jewel during no load hours is possible since it is a common practice to keep the meter that is in service excited with the line potential at all times.

This new and startling observation, the correctness of which has been proved so convincingly by Mr. Holtz, both by calculations and by ingenious experiments, will be of particular importance in giving a guide in the replacement of jewel bearings. It will, no doubt, also have an effect upon the design of the jewel bearings and possibly upon the design of the meter. Mr. Holtz's work represents an important scientific step in the exploration of the behavior of watt-hour meter jewel bearings, and it is hoped that more of this type of work will be done in the future until we have a clear conception of all the factors entering into the design of a satisfactory lower bearing for watt-hour meters.

There is one factor which may enter into this picture so as to reduce the excessive wear at no load. This reduction of wear may come about by a slight wearing of the jewel at the spot at which the pivot point rests during no load. The slightly increased friction may reduce this no load motion of the pivot to zero and when the load is placed on the meter, the pivot point, due to the side thrust, will be drawn away from the no load position and will slide or glide on a smooth, unworn part of the jewel cup. This side thrust, which is very large in the modern high-torque watt-hour meter, brings in new problems in the design of the bearing, and it is hoped that Mr. Holtz will continue his excellent work and thus give us more and more information of real value for the design, selection, and maintenance of the watt-hour meter jewel bearing.

J. H. Goss (General Electric Company, West Lynn, Mass.): The author points out that the phenomenon of vibration of an a-c watt-hour meter moving element under potential excitation alone has been generally recognized. The method of study of the vibration developed by the author is both novel and effective.

One effect of the vibration of the moving element is to reduce the friction in the register, top bearing, and bottom bearing. In fact the friction is reduced to the point that but a small fraction of the torque of the light-load compensating adjustment is required for it. The remainder is needed to correct the unbalance in the electromagnetic element and to compensate for the current iron permeability characteristic.

The equation of wear, $W=T+R+f(T,R)$, was set up for the pivot bearing. For a lubricated pivot bearing the wear of the pivot tends to reach a constant value as shown in a previous AIEE paper ("Lubrication Increases Life of Meter Bearings," T. A. Abbott and J. H. Goss, Electrical Engineering (AIEE Transactions), volume 54, April 1935, pages 428–31). This has been confirmed by actual tests both with watt-hour meters running under load and watt-hour meters operated with potential excitation only. The watt-hour meters operated with potential excitation only actually showed less wear by an appreciable amount than those operated under a moderate load.

The above equation would not represent the condition of wear of a well-lubricated pivot bearing, as neither the term T nor R is linear.

The author points out that in the case of the ball bearing with potential excitation only, a condition of true rolling exists. It is interesting to observe the motion of the ball in a watt-hour meter bearing under actual load conditions. This is possible if a microscope with a magnification of approximately 40 diameters is used. The ball spins erratically as the load changes and presents new points of contacts to the sapphire cups. This renews the actual bearing surfaces and coupled with the rolling action under condition of potential excitation only, no doubt accounts for the performance of the ball-type bearing operating without lubrication.

Paul MacGahan (Westinghouse Electric and Manufacturing Company, Newark, N. J.): This very timely paper by F. C. Holtz is of prime interest, both to the specialists in the field of metering and to the electrical industry in general.

The electrical industry depends entirely upon the registration of the meter for the wherewithal for its development—for its very existence, in fact. Thus, until a practical a-c meter was invented in 1888, the industry could not be financed to proceed beyond the narrow confines of the d-c system. Therefore, any factors contributing to the accuracy and permanence of the meters are of general interest to all concerned.

The reading of the paper discloses that the author is concerned with the vibratory motion of the moving element when excited by the simple single-phase magnetic field due to the voltage coil. This field induces corresponding secondary currents in the disk which do not produce rotation but only an oscillation due to harmonic attraction and repulsion.

Mr. Holtz has, in a very interesting manner, analyzed this condition by the aid of modern methods, both in theory and by laboratory. The conclusions are that the ball bearing should perform better than the pivot type in watt-hour meters.

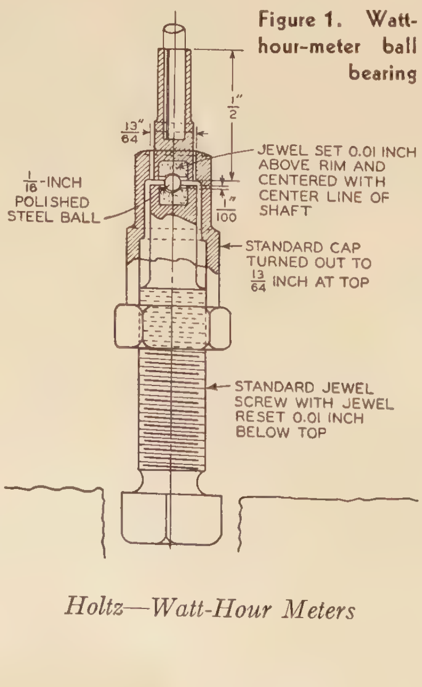

Figure 1. Watt-hour-meter ball bearing

Mr. Holtz correctly assumes that all meter engineers know the early history of this development. For the benefit of other engineers not intimately associated with the American meter art, it would seem desirable to add the following brief account of the early history.

The year 1897 brought forth the original so-called "round type" Westinghouse induction-type watt-hour meter. This meter was characterized by the use of a very light moving element and a high ratio of torque to weight, compared to earlier forms. It was small, and in many ways, a distinct advance in the art. The meter was designed by Doctor Frank Conrad and H. P. Davis.

The largest of the early utilities in the a-c field was the United Electric Light and Power Company of New York City, now a part of the Consolidated Edison Company. Mr. Davis' field investigations with W. E. McCoy of the United company led to a suggestion from Mr. McCoy that it would be desirable to use a readily replaceable pivot in the form of a small steel ball.

The year 1902 found the writer engaged as assistant to Frank Conrad in the design of watt-hour meters and instruments. At that time, we had just produced and put on the market an improved form of the original meter using a front-connected terminal chamber and improved means of adjustment.

The writer was directed to have experimental models designed and made, using ball bearings. Tests made by us brought out the fact that vibration in the moving element was causing the pivot bearings to wear rather fast. It took but the sense of touch and a magnifying glass to discover this vibration and to note that it existed even with only the voltage coil connected.

Figure 1 is a reproduction of a drawing based on the original freehand sketch, dated 1902, of the experimental ball bearing as finally decided on. This design comprised the use of a steel ball between two sapphire jewels. The idea was to avoid the wear of pivots because of vibration and rubbing friction, by substituting a rolling action.

The writer recollects considerable discussion on the question of whether the ball actually rolled or whether it only turned like a pivot. The claims that it rolled were questioned in a letter to the editor of *Electrical World*, by William Hallock (see page 700, *Electrical World*, October 21, 1905). To this, the writer replied, giving an explanation of the reason for the rolling action (see *Electrical World*, November 11, 1905, page 827).

It is interesting to note that today, 37 years later, the ball which is used is exactly the same as the one selected in 1902 as being the most suitable in size and quality for this purpose.

This ball bearing was introduced as a further improvement in the so-called sub *A* Davis-Conrad meter in the year 1902.

Another advantage soon became apparent, which was that this bearing did not need any lubrication whatever. In fact, it worked better dry than oiled.

While practically all the meters of the 1902 vintage have been replaced by modern types, many cases are on record of continu-

Transformation Theory of General Static Polyphase Networks

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Synopsis: Starting from the canonical equations of a general, linear, bilateral network and by the application of transformation matrices, giving the various current constraints in typical polyphase systems, equations are obtained which give the response of the most general wye-wye, delta-delta, and delta-wye static systems to arbitrary electromotive forces at the sending and receiving ends. Mutual inductances and capacitances are assumed between the various branches of the circuits.

The paper is concluded with a brief exposition of the method of symmetrical components from the transformation point of view and an application to the general wye-wye circuit is given as an example.

THERE has been considerable work recently in the application of tensors, dyadics, and matrices to electric circuit theory by Kron, Bewley, Sah, Reed, and others. The problem of general static polyphase systems in the steady and transient states does not seem to have been treated. It appears that the great power of these methods is nowhere more evident than when general systems are considered. Once having obtained the solution of these general systems, the solution of simpler ones come under special cases.

In the interest of such generalizations, and to illustrate the power and simplicity of matrix algebra in this class of problems, the study presented in this paper was undertaken.

The properties of matrices given in the paper "Matrices in Engineering" by Pipes[1] will be assumed in the following discussion.

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1. For all numbered references, see list at end of paper.

I. Notation

For simplicity, the following notation will be used:

Instantaneous values of currents and voltages will be denoted by small letters i_n, e_n, etc. Matrices whose elements are instantaneous values of currents and voltages will be denoted by $[i]$ and $[e]$ respectively.

Impedance operators of the form $z_{mn}=L_{mn}d/dt+R_{mn}+S_{mn}\int_{\infty}^{t}(\ )dt$ will be denoted by small z's, and matrices whose elements are impedance operators of the above form will be denoted by $[z]$.

Complex currents and voltages will be denoted by I_n and E_n respectively, and matrices whose elements are complex currents and voltages will be denoted by $[I]$ and $[E]$.

Complex impedance and admittance operators will be denoted by $Z_{mn}=jwL_{mn}+R_{mn}+S_{mn}/jw$ and Y_{mn} respectively. Matrices whose elements are complex impedance and admittance operators will be denoted by $[Z]$ and $[Y]$. This symbolism appears to be simple and convenient.

II. General Transformation Theory

Consider a general n-mesh circuit. Let the n mesh currents have the instantaneous values $(i_1, i_2, \ldots i_n)$ and let there be n voltages, $(e_1, e_2, \ldots e_n)$ acting on the contours of the n meshes. The canonical equations of such a general n mesh circuit may be written in the form:

$$[e]=[z][i] \tag{1}$$

where $[e]$ and $[i]$ are columnar matrices whose elements are the n mesh voltages and currents respectively and $[z]$ is a square matrix of the nth order whose elements are the various self- and mutual-impedance operators.

If we let ϕ_s be the total flux linkage with respect to mesh s due to all the self and mutual inductances on its contour, we have:

$$[\phi]=[L][i] \tag{2}$$

In this equation $[\phi]$ is a columnar matrix whose elements are the respective flux linkages of the n meshes and $[L]$ is a square matrix of the nth order whose elements are the self- and mutual-inductance coefficients of the circuit.

If T is the total instantaneous magnetic energy of the system, then:

$$T=[i]'[\phi]/2 \tag{3}$$

where $[i]'$ is the transpose of $[i]$.

Substituting the expression in (2) for $[\phi]$ into (3) we obtain:

$$T=\frac{[i]'[L][i]}{2} \tag{4}$$

If we let $(e_{c1} \ldots e_{cn})$ be the capacitance voltages induced on the conductors of the respective meshes, we have:

$$[e_c]=[S][q] \tag{5}$$

In this equation, $[S]$ is a square matrix of the nth order whose elements are the self- and mutual-elastance coefficients of the system. $[q]$ is a columnar matrix of the n mesh charges defined by:

$$[q]=\int_{-\infty}^{t}[i]dt \tag{6}$$

Now if V is the total instantaneous electrostatic energy of the system, we have:

$$V=\frac{[q]'[e_c]}{2} \tag{7}$$

where $[q]'$ is the transpose of $[q]$.

Substituting (5) into (7), we obtain:

$$V=\frac{[q]'[S][q]}{2} \tag{8}$$

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ous operation of various ball bearing meters for 20 years or over without requiring any replacement of the bearings and without any lubrication problems.

F. C. Holtz: In replying to the remarks made by Mr. Goss, the author wishes to state that the equations of wear were, unfortunately, not a rigorous treatment of the subject. Both T and R should be some undetermined function of the time and revolutions respectively. In fact, even such representation may not be sufficient to explain a mass of observed data.

The part which vibration plays in reducing the friction of a meter register and other moving parts is most interesting and is probably responsible for the very uniform performance of watt-hour meters at light load. The presence of vibration was not recognized in some of the earlier forms of watt-hour meters; however, its advantages were appreciated and special devices were employed to produce sufficient vibration to maintain the moving system in a state of motion.

Mr. Knopp has pointed out in his remarks that a slight increase in friction may be sufficient completely to arrest the motion of the moving system. This has not been observed in lubricated pivot-type meters even after several years' operation; however, it is probably true that the motion was considerably reduced. It would be interesting to study the problem from this angle and determine under what conditions the motion could be arrested. Furthermore, as pointed out by Mr. Goss, certain advantages result from keeping the moving system in a state of vibration.

Letting the induced voltages due to the resistances on the various mesh contours of the system be $(e_{r1} \ldots e_{rn})$, we have:

$$[e_r] = [R][i] \tag{9}$$

Here $[R]$ is a square matrix of the nth order whose elements are the various mutual and self-resistance coefficients of the several meshes.

If we let F be the total instantaneous rate of energy loss of the circuit, we have:

$$F = [i]'[e_r] \tag{10}$$

Substituting (9) into (10), we have:

$$F = [i]'[R][i] \tag{11}$$

Consider now that the original n-mesh system is interconnected in some manner to form a transformed system. By the transformation there will be formed new meshes and consequently new mesh currents will be required to specify the transformed system.

Let the matrix of the new mesh currents be $[i]_n$, and let the new currents be related to the old currents by means of the transformation matrix $[A]$ which need not be nonsingular. That is:

$$[i] = [A][i]_n \tag{12}$$

In general, $[A]$ is an n-rowed matrix of constants.

Now in the new system, the form of the expressions:

$$T = \frac{[i]'[L][i]}{2} \tag{4}$$

$$V = \frac{[q]'[S][q]}{2} \tag{8}$$

$$F = [i]'[R][i] \tag{11}$$

must be preserved, and we must have:

$$T_n = [i]_n'[L]_n[i]_n/2 \tag{13}$$

$$V_n = [q]_n'[S]_n[q]_n/2 \tag{14}$$

$$F_n = [i]_n'[R]_n[i]_n \tag{15}$$

for the instantaneous magnetic energy, electrostatic energy, and power dissipation in the new system. Here $[L]_n$ is the new inductance matrix, $[S]_n$, the new elastance matrix, and $[R]_n$, the new resistance matrix.

To obtain the transformations of the new quantities from the old ones we use the equations:

$$[i] = [A][i]_n \tag{12}$$

$$[q] = [A][q]_n \tag{6}$$

Now, by one of the fundamental theorems of matrix algebra we have:

$$[i]' = ([A][i]_n)' = [i]_n'[A]' \tag{16}$$

$$[q]' = ([A][q]_n)' = [q]_n'[A]' \tag{17}$$

Substituting these expressions into the equations 4, 8, and 11, we obtain for the new network:

$$T_n = [i]_n'[A]'[L][A][I]_n/2 \tag{13}$$

$$V_n = [q]_n'[A]'[A][A][q]_n/2 \tag{14}$$

$$F_n = [i]_n'[A]'[R][A][i]_n \tag{15}$$

Hence if we place:

$$[L]_n = [A]'[L][A] \tag{18}$$

$$[S]_n = [A]'[S][A] \tag{19}$$

$$[R]_n = [A]'[R][A] \tag{20}$$

we preserve the form of the energy equations. We see that the new inductance, elastance, and resistance matrices are obtained from the old inductance, elastance, and resistance matrices by the same type of transformation involving the matrix $[A]$ and its transpose.

Transformation of the Impedance Matrix

The transformation of the impedance matrix is easily obtained by noting that:

$$[z]_n = [L]_n\frac{d}{dt} + [R]_n + [S]_n \int_{-\infty}^{t} (\ )dt \tag{21}$$

and

$$[z] = [L]\frac{d}{dt} + [R] + [S] \int_{-\infty}^{t} (\ )dt \tag{22}$$

In view of (18), (19), and (20), we see that:

$$[z]_n = [A]'[z][A] \tag{23}$$

is the transformation equation for the impedance operator matrix.

Transformation of the Mesh Voltages

In the new system, the canonical equations of the circuit may be written in the matrix form:

$$[e]_n = [z]_n[i]_n \tag{24}$$

or, in view of (23)

$$[e]_n = [A]'[z][A][i]_n \tag{25}$$

But

$$[i] = [A][i]_n \tag{12}$$

Hence:

$$[e]_n = [A]'[z][i] \tag{26}$$

However, by (1) $[e] = [z][i]$, therefore:

$$[e]_n = [A]'[e] \tag{27}$$

This is the transformation formula for the mesh voltages.

Transformation of Complex Quantities

Since the complex currents and voltages differ from the instantaneous currents and voltages only by scalar multiplicative phase constants, and the complex impedances differ from the impedance operators in that d/dt is replaced by jw and $\int_{-\infty}^{t} (\ )dt$ by $1/jw$, we see that these quantities transform in the same manner that the scalar instantaneous quantities transform, and hence we have that if:

$$[I] = [A][I]_n \tag{28}$$

that is, the complex voltages of the new system are linearly related to the complex voltages of the original system by the transformation matrix $[A]$, then:

$$[Z]_n = [A]'[Z][A] \tag{29}$$

and

$$[E]_n = [A]'[E] \tag{30}$$

III. Application to the General Wye-Wye Circuit

Let us apply the above theory to obtain the performance of the general wye-wye circuit of figure 1. For generality, we shall consider mutual inductance and capacitance between the three sending-end impedances, the four line impedances, and the three receiving-end impedances. We shall also assume that there are impressed voltages in series with the three sending-end impedances and the three receiving-end impedances.

The completed wye-wye circuit may be considered as made up by the synthesis of a ten-mesh network whose canonical equation is:

$$[e] = [z][i] \tag{1}$$

where:

$$[e] = \begin{array}{c} a \\ b \\ c \\ r \\ s \\ t \\ n \\ 1 \\ 2 \\ 3 \end{array} \begin{Vmatrix} e_a \\ e_b \\ e_c \\ 0 \\ 0 \\ 0 \\ 0 \\ e_1 \\ e_2 \\ e_3 \end{Vmatrix} \qquad [i] = \begin{array}{c} a \\ b \\ c \\ r \\ s \\ t \\ n \\ 1 \\ 2 \\ 3 \end{array} \begin{Vmatrix} i_a \\ i_b \\ i_c \\ i_r \\ i_s \\ i_t \\ i_n \\ i_1 \\ i_2 \\ i_3 \end{Vmatrix}$$

$$[z] = \begin{array}{c|cccccccccc} & a & b & c & r & s & t & n & 1 & 2 & 3 \\ \hline a & z_{aa} & z_{ab} & z_{ac} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ b & z_{ba} & z_{bb} & z_{bc} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ c & z_{ca} & z_{cb} & z_{cc} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ r & 0 & 0 & 0 & z_{rr} & z_{rs} & z_{rt} & z_{rn} & 0 & 0 & 0 \\ s & 0 & 0 & 0 & z_{sr} & z_{ss} & z_{st} & z_{sn} & 0 & 0 & 0 \\ t & 0 & 0 & 0 & z_{tr} & z_{ts} & z_{tt} & z_{tn} & 0 & 0 & 0 \\ n & 0 & 0 & 0 & z_{nr} & z_{ns} & z_{nt} & z_{nn} & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & z_{11} & z_{12} & z_{13} \\ 2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & z_{21} & z_{22} & z_{23} \\ 3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & z_{31} & z_{32} & z_{33} \end{array}$$

This ten-mesh network is transformed into the wye-wye circuit of figure 1 by

interconnection. When the original network is interconnected, new meshes are formed and the old currents undergo certain constraints. If we let (i_a', i_b', i_c') be the currents flowing through the impedances z_{aa}, z_{bb}, and z_{cc} in the transformed network, we have the following equations giving the current constraints imposed on the old currents by the interconnection.

$$\left.\begin{array}{llll} i_a=i_a' & i_r=i_a' & i_t=i_c' & i_2=-i_b' \\ i_b=i_b' & i_s=i_b' & i_n=-(i_a'+i_b'+i_c') & \\ i_c=i_c' & & i_1=-i_a' & i_3=-i_c' \end{array}\right\} \quad (31)$$

That is, the old currents are linearly related to the new currents by the transformation matrix $[A]$, where in this case:

$$[A]=\begin{array}{c} \\ a \\ b \\ c \\ r \\ s \\ t \\ n \\ 1 \\ 2 \\ 3 \end{array}\begin{array}{c} \begin{array}{ccc} a' & b' & c' \end{array} \\ \left\|\begin{array}{ccc} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ -1 & -1 & -1 \\ -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{array}\right\| \end{array} \quad (32)$$

$$[A]'=\left\|\begin{array}{cccccccccc} 1 & 0 & 0 & 1 & 0 & 0 & -1 & -1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 & -1 & 0 & -1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 & -1 & 0 & 0 & -1 \end{array}\right\| \quad (33)$$

We now compute the new impedance matrix by means of the equation:

$$[z]_n=[A]'[z][A] \quad (23)$$

By direct multiplication, we have:

$$[z]_n=\left\|\begin{array}{ccc} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{array}\right\| \quad (34)$$

where:

$$a_{11}=(z_{aa}+z_{rr}-2z_{nr}+z_{nn}+z_{11})$$
$$a_{22}=(z_{bb}+z_{ss}-2z_{ns}+z_{nn}+z_{22})$$
$$a_{33}=(z_{cc}+z_{tt}-2z_{nt}+z_{nn}+z_{33})$$
$$a_{12}=(z_{ab}+z_{rs}-z_{rn}-z_{ns}+z_{nn}+z_{12})=a_{21}$$
$$a_{13}=(z_{ac}+z_{rt}-z_{rn}-z_{nt}+z_{nn}+z_{13})=a_{31}$$
$$a_{23}=(z_{bc}+z_{st}-z_{sn}-z_{nt}+z_{nn}+z_{23})=a_{32}$$

We note that the new impedance matrix is symmetric. The new voltages are transformed by the equation:

$$[e]_n=[A]'[e] \quad (27)$$

In this case, by direct multiplication, we obtain:

$$[e]_n=\left\|\begin{array}{c} (e_a-e_1) \\ (e_b-e_2) \\ (e_c-e_3) \end{array}\right\| \quad (35)$$

We then have:

$$[e]_n=[z]_n[i]_n \quad (24)$$

or:

$$[i]_n=[z]_n^{-1}[e]_n \quad (36)$$

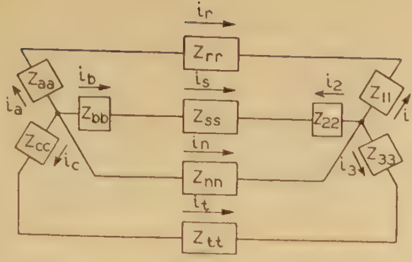

Figure 1. General wye-wye circuit

Z_{ab} is the mutual impedance between Z_{aa} and Z_{bb}, etc.

or placing:

$$[y]_n=[z]_n^{-1} \quad (37)$$

we have:

$$[i]_n=[y]_n[e]_n \quad (38)$$

Calculating the inverse of the matrix (34), we obtain:

$$[y]_n=\frac{1}{D}\left\|\begin{array}{ccc} (a_{22}a_{23}-a_{32}^2) & (a_{32}a_{13}-a_{12}a_{33}) & (a_{12}a_{23}-a_{22}a_{13}) \\ (a_{31}a_{23}-a_{21}a_{33}) & (a_{11}a_{33}-a_{13}^2) & (a_{21}a_{13}-a_{11}a_{23}) \\ (a_{21}a_{32}-a_{31}a_{22}) & (a_{31}a_{12}-a_{11}a_{32}) & (a_{11}a_{22}-a_{12}^2) \end{array}\right\| \quad (39)$$

and D is the determinant

$$D=\left|\begin{array}{ccc} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{array}\right|$$

we note that the matrix $[y]_n$ is symmetric.

The currents in the various elements are now obtained from:

$$[i]=[A][i]_n \quad (12)$$

The equation $[e]_n = [Z]_n[i]_n$ may be given a rather interesting physical interpretation. If we write:

$$[e]_s=\left\|\begin{array}{c} e_a \\ e_b \\ e_c \end{array}\right\| \quad (40) \qquad [e]_r=\left\|\begin{array}{c} e_1 \\ e_2 \\ e_3 \end{array}\right\| \quad (41)$$

$$[z]_s=\left\|\begin{array}{ccc} z_{aa} & z_{ab} & z_{ac} \\ z_{ba} & z_{bb} & z_{bc} \\ z_{ca} & z_{cb} & z_{cc} \end{array}\right\| \quad (42)$$

$$[z]_r=\left\|\begin{array}{ccc} z_{11} & z_{12} & z_{13} \\ z_{21} & z_{22} & z_{23} \\ z_{31} & z_{32} & z_{33} \end{array}\right\| \quad (43)$$

$$[z]_L=\left\|\begin{array}{ccc} (z_{rr}-2z_{rn}+z_{nn}) & (z_{rs}-z_{rn}-z_{ns}+z_{nn}) & (z_{rt}-z_{rn}-z_{nt}+z_{nn}) \\ (z_{sr}-z_{sn}-z_{nr}+z_{nn}) & (z_{ss}-2z_{sn}+z_{nn}) & (z_{st}-z_{sn}-z_{nt}+z_{nn}) \\ (z_{tr}-z_{tn}-z_{nr}+z_{nn}) & (z_{ts}-z_{tn}-z_{ns}+z_{nn}) & (z_{tt}-2z_{nt}+z_{nn}) \end{array}\right\| \quad (44)$$

Then, we may write:

$$[e]_s=[z]_s[i]_n+[z]_L[i]_n+[z]_r[i]_n+[e]_r \quad (45)$$

This equation is the same as that of a simple series circuit with the exception that the ordinary voltages, impedances, and current are replaced by matrix quantities.

The Steady State

In the above analysis, we have considered the transformation of the instantaneous voltages, currents, and the impedance operators. In case the impressed voltages at the sending and receiving ends are sinusoidal quantities of arbitrary phase, all the foregoing equations hold when the instantaneous voltage matrix, $[e]$, is replaced by the vector voltage matrix, $[E]$, the instantaneous current matrix, $[i]$, is replaced by the vector current matrix, $[I]$, and the impedance operator matrix, $[z]$, is replaced by the complex impedance matrix, $[Z]$.

We have, then, the equation:

$$[I]_n=[Z]^{-1}[E]_n=[Y]_n[E]_n \quad (46)$$

for the determination of the vector currents in terms of the complex admittance matrix and the complex voltage matrix. The impedance matrix $[Y]_n$ is given by (39) where the a's have the values given in (34) and the z's are replaced by the Z's or complex impedance operators.

Transient Disturbances (General Electromotive Forces)

Having obtained the equation of the circuit in the canonical form:

$$[e]_n=[z]_n[i]_n \quad (24)$$

we may proceed to find the response of the circuit to the effect of arbitrary electromotive forces impressed at $t=0$ by the use of the Laplacian transformation (see reference 2). In order to do this,

$$[E(p)]_n=p\int_0^\infty e^{-pt}[e]_n dt \quad (47)$$

$$[I(p)]_n=p\int_0^\infty e^{-pt}[i]_n dt \quad (48)$$

Then if we take (24) and multiply both sides by $pe^{-pt}dt$ and integrate them from zero to infinity, we have:

$$p\int_0 e^{-pt}[e]_n dt=p\int_0^\infty e^{-pt}[z]_n[i]_n dt \quad (49)$$

Now since:

$$[z]_n=[L]_n\frac{d}{dt}+[R]_n+[S]_n\int_{-\infty}^t (\ )dt \quad (21)$$

we may transform (49) by integrating by parts and we obtain:

$$[Z(p)]_n[I(p)]_n=[E(p)]_n+p[L]_n[i^0]_n-[S]_n[q^0]_n \quad (50)$$

where $[i^0]_n$ is a columnar matrix giving the initial currents in the mesh inductances at $t = 0$. $[q^0]_n$ is a columnar matrix giving the initial charges in the mesh elastances at $t = 0$. $[Z(p)]$ is a matrix whose elements are:

$$Z_{mn} = pL_{mn} + R_{mn} = S_{mn}/p \qquad (51)$$

If we multiply (50) by $[Z(p)]_n^{-1}$, we get:

$$[I(p)]_n = [Z(p)]_n^{-1}([E(p)]_n + p[L]_n[i^0]_n - [S]_n[q^0]_n) \qquad (52)$$

Now, by means of the Fourier-Mellin inversion formula, we have an explicit expression for the instantaneous current matrix:

$$[i(t)]_n = \frac{1}{2\pi j}\int_{c-j\infty}^{c+j\infty} \frac{e^{pt}[I(p)]_n dt}{p} \qquad (53)$$

and we have a formal solution for the circuit currents when arbitrary electromotive forces, initial currents, and initial charges are impressed upon the circuit at $t=0$.

IV. The Delta-Delta Circuit

We shall now carry out a similar treatment of the general delta-delta circuit shown in figure 2. We shall consider electromotive forces in series with the three delta-connected impedances at the sending end, electromotive forces in series with the three delta-connected impedances at the receiving end, and also mutual inductances and capacitances will be assumed between the three sending-end impedances, the three receiving-end impedances, and the three line impedances.

The delta-delta circuit may be considered as made up by the synthesis of a nine-mesh circuit which is interconnected to form the required four-mesh delta-delta circuit.

The impedance matrix of the original nine-mesh circuit is:

$$[z] = \begin{Vmatrix} z_{aa} & z_{ab} & z_{ac} & 0 & 0 & 0 & 0 & 0 & 0 \\ z_{ba} & z_{bb} & z_{bc} & 0 & 0 & 0 & 0 & 0 & 0 \\ z_{ca} & z_{cb} & z_{cc} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & z_{rr} & z_{rs} & z_{rt} & 0 & 0 & 0 \\ 0 & 0 & 0 & z_{sr} & z_{ss} & z_{st} & 0 & 0 & 0 \\ 0 & 0 & 0 & z_{tr} & z_{ts} & z_{tt} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & z_{11} & z_{12} & z_{13} \\ 0 & 0 & 0 & 0 & 0 & 0 & z_{21} & z_{22} & z_{23} \\ 0 & 0 & 0 & 0 & 0 & 0 & z_{31} & z_{32} & z_{33} \end{Vmatrix} \qquad (54)$$

In order to specify the interconnected delta-delta circuit, we shall use the four mesh currents (i_1', i_2', i_3', i_4') shown in figure 2. The elements of the transformation matrix, $[A]$, are obtained from the set of equations:

$$\begin{array}{lll} i_a = i_1' - i_3' & i_r = i_3' & i_1 = i_2' + i_3' \\ i_b = i_1' - i_4' & i_s = i_4' - i_3' & i_2 = i_2' + i_4' \\ i_c = i_1' & i_t = -i_4' & i_3 = i_2' \end{array} \qquad (55)$$

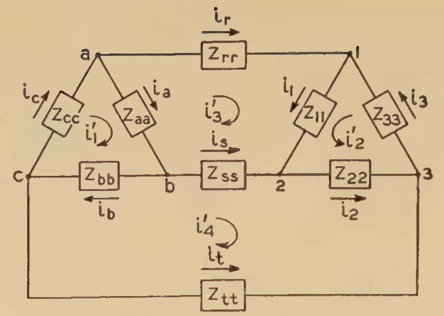

Figure 2. General delta-delta circuit

Hence the transformation matrix is:

$$[A] = \begin{Vmatrix} 1 & 0 & -1 & 0 \\ 1 & 0 & 0 & -1 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & -1 & 1 \\ 0 & 0 & 0 & -1 \\ 0 & 1 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & 1 & 0 & 0 \end{Vmatrix} \qquad (56)$$

$$[A]' = \begin{Vmatrix} 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\ -1 & 0 & 0 & 1 & -1 & 0 & 1 & 0 & 0 \\ 0 & -1 & 0 & 0 & 1 & -1 & 0 & 1 & 0 \end{Vmatrix} \qquad (57)$$

By direct multiplication using the equation:

$$[z]_n = [A]'[z][A], \qquad (23)$$

we obtain

$$[z]_n = \begin{Vmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{Vmatrix} \qquad (58)$$

where:

$$a_{11} = z_{aa} + z_{bb} + z_{cc} + 2z_{ab} + 2z_{ac} + 2z_{bc}$$
$$a_{22} = z_{11} + z_{22} + z_{33} + 2z_{12} + 2z_{13} + 2z_{23}$$
$$a_{33} = z_{aa} + z_{rr} + z_{ss} + z_{11} - 2z_{rs}$$
$$a_{44} = z_{bb} + z_{ss} + z_{tt} + z_{22} - 2z_{ts}$$
$$a_{12} = a_{21} = 0$$
$$a_{13} = -(z_{aa} + z_{ba} + z_{ca}) = a_{31}$$
$$a_{14} = -(z_{ab} + z_{bb} + z_{cb}) = a_{41}$$
$$a_{23} = z_{11} + z_{21} + z_{31} = a_{32}$$
$$a_{24} = z_{12} + z_{22} + z_{32} = a_{42}$$
$$a_{34} = z_{ab} + z_{rs} - z_{ss} + z_{st} - z_{rs} + z_{12} = a_{43}$$

The original voltage matrix is:

$$[e] = \begin{Vmatrix} e_a \\ e_b \\ e_c \\ 0 \\ 0 \\ 0 \\ e_1 \\ e_2 \\ e_3 \end{Vmatrix} \qquad (59)$$

$$[e]_n = [A]'[e] = \begin{Vmatrix} (e_a + e_b + e_c) \\ (e_1 + e_2 + e_3) \\ (-e_a + e_1) \\ (-e_b + e_2) \end{Vmatrix} \qquad (60)$$

The transformed voltage matrix.

We now have:

$$[i]_n = [z]_n^{-1}[e]_n \qquad (36)$$

the formal expression for the various mesh currents.

The treatment for the steady-state and transient behavior may be carried out in the manner discussed in part III.

V. The Delta-Wye Circuit

Let us consider the delta-wye circuit shown in figure 3. As in the above examples, we may consider this circuit as made up by the synthesis of a nine-mesh circuit whose impedance matrix is given by (54).

The delta-wye circuit will be specified by the three mesh currents (i_1', i_2', i_3') as shown in the figure. In this case, the elements of the transformation matrix are given by the set of equations giving the following current constraints:

$$\begin{array}{lll} i_a = i_1' - i_2' & i_r = i_2' & i_1 = i_2' \\ i_b = i_1' - i_3' & i_s = i_3' - i_2' & i_2 = i_2' - i_3' \\ i_c = i_1' & i_t = -i_3' & i_3 = i_3' \end{array}$$

Hence we have the following transformation matrix:

$$[A] = \begin{Vmatrix} 1 & -1 & 0 \\ 1 & 0 & -1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & -1 & 1 \\ 0 & 0 & -1 \\ 0 & -1 & 0 \\ 0 & 1 & -1 \\ 0 & 0 & 1 \end{Vmatrix} \qquad (62)$$

$$[A]' = \begin{Vmatrix} 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 1 & -1 & 0 & -1 & 1 & 0 \\ 0 & -1 & 0 & 0 & 1 & -1 & 0 & -1 & 1 \end{Vmatrix} \qquad (63)$$

By the equation:

$$[z]_n = [A]'[a][A] \qquad (23)$$

we obtain the transformed matrix:

$$[z]_n = \begin{Vmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{Vmatrix} \qquad (64)$$

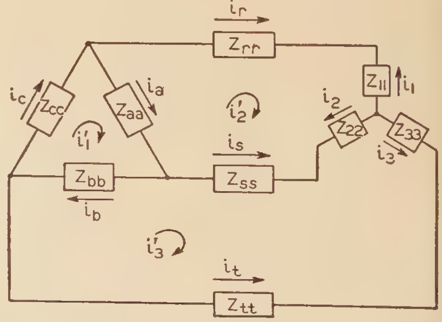

Figure 3. General delta-wye circuit

where:

$$
\begin{aligned}
a_{11} &= z_{aa}+z_{bb}+z_{cc}+2z_{ab}+2z_{ca}+2z_{cb} \\
a_{22} &= z_{aa}+z_{rr}+z_{ss}+z_{22}-2z_{sr}-2z_{12}+z_{11} \\
a_{33} &= z_{bb}+z_{ss}+z_{tt}+z_{22}+z_{33}-2z_{ts}-2z_{23} \\
a_{12} &= -(z_{aa}+z_{ab}+z_{ac})=a_{21} \\
a_{13} &= -(z_{ab}+z_{bb}+z_{cb})=a_{31} \\
a_{23} &= (z_{ab}+z_{rs}-z_{ss}-z_{rt}+z_{st}+z_{12}-z_{22}-z_{13}+ \\
&\qquad z_{23})=a_{32}
\end{aligned} \tag{65}
$$

The inverse matrix:

$$[y]_n=[z]_n^{-1} \tag{37}$$

is given in terms of the a's by (39) where in this circuit, the a's have the values given by (65).

In this case, the original voltage matrix is given by (59) and by the transformation we obtain:

$$[e]_n=[A]'[e]=\left\|\begin{matrix}(e_a+e_b+e_c)\\(e_2-e_a-e_1)\\(e_3-e_b-e_2)\end{matrix}\right\| \tag{66}$$

The various mesh currents are given by:

$$[i]_n=[z]_n^{-1}[e]_n \tag{36}$$

and the solution for the steady state or the transient behavior follows the same reasoning of part III.

It is noted that by considering these general cases, we have covered all possible combinations of delta and wye connections. In the case that the circuits have balanced impedances and voltages, considerable simplifications are effected in the above general equations. In case even more general circuits are considered, the matrices of the original nine or ten mesh circuits whose synthesis produce the required circuits would have mutual impedances between every mesh. The synthesis of such networks would produce polyphase systems having coupling between every elements. The amount of coupling considered here is sufficiently general for practical purposes.

VI. Symmetrical Components

The discussion will be concluded with a brief consideration of the transformation theory of the method of symmetrical components. Since the method of symmetrical components is one of linear transformation, it lends itself readily to matrix formulation.

In the method of symmetrical components, the transformations are effected by the use of the nonsingular, symmetric matrix:

$$[S]=\left\|\begin{matrix}1 & 1 & 1 & \cdot & \cdot & \cdot & 1\\ 1 & a^{-1} & a^{-2} & \cdot & \cdot & \cdot & a^{-(n-1)}\\ 1 & a^{-2} & a^{-4} & \cdot & \cdot & \cdot & a^{-2(n-1)}\\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot\\ 1 & a^{-(n-1)} & a^{-2(n-1)} & \cdot & \cdot & \cdot & a^{-(n-1)(n-1)}\end{matrix}\right\| \tag{67}$$

where:

$$a=\epsilon^{2\pi j/n} \tag{68}$$

The matrix $[S]$ may be written more briefly in the manner:

$$[S]=\left\|\begin{matrix}S_0\\S_{-1}\\S_{-2}\\-\\S_{-(n-1)}\end{matrix}\right\| \tag{69}$$

where:

$$S_{-r}=(1,\ a^{-r},\ a^{-2r},\ \ldots\ a^{-(n-1)r}) \tag{70}$$

is the same as Fortescue's sequence operator S^r.

Fundamental Properties of [S]

Inspection of the matrix $[S]$, reveals that it has the following important properties:

$$[S]'=[S] \tag{71}$$

where $[S]$ is the transpose of $[S]$

$$[S]^{-1}=\frac{1}{n}[\bar{S}] \tag{72}$$

where $[S]^{-1}$ is the inverse of $[S]$ and $[\bar{S}]$ is the conjugate of $[S]$ given by:

$$[\bar{S}]=\left\|\begin{matrix}S_0\\S_1\\S_2\\-\\S_{(n-1)}\end{matrix}\right\|$$

and n is the order of $[S]$.

Transformation of Voltages and Currents

Let the ordinary complex voltages and currents of an n-phase network be written in the form:

$$[I]=\left\|\begin{matrix}I_1\\I_2\\-\\I_n\end{matrix}\right\| \tag{73}\qquad [E]=\left\|\begin{matrix}E_1\\E_2\\ \\E_n\end{matrix}\right\| \tag{74}$$

and let $[I]_s$ and $[E]_s$ be the symmetrical components of current and voltage respectively. They are specified by the equations:

$$[i]=[S][I]_s \tag{75}$$

$$[E]=[S][E]_s \tag{76}$$

Or, since $[S]$ is a nonsingular matrix, its inverse exists and we have:

$$[I]_s=[S]^{-1}[i]=\frac{1}{n}[\bar{S}][I] \tag{77}$$

$$[E]_s=[S]^{-1}[E]=\frac{1}{n}[\bar{S}][E] \tag{78}$$

Transformation of Impedances and Admittances

The impedance matrix $[Z]$ associated with the ordinary currents $[I]$ and the ordinary voltages $[E]$ satisfies the equation:

$$[E]=[Z][I] \tag{79}$$

or

$$[S][E]_s=[Z][S][I]_s \tag{80}$$

Hence:

$$[E]_s=[S]^{-1}[Z][S][I]_s \tag{81}$$

If we place:

$$[Z]_s=[S]^{-1}[Z][S] \tag{82}$$

the symmetrical component matrix, then we have:

$$[E]_s=[Z]_s[I]_s \tag{83}$$

the voltage equation in symmetrical components.

From (82) we see that $[Z]_s$ is obtained from $[S]$ by a similarity transformation. We have also the reciprocal relation:

$$[Z]=[S][Z]_s[S]^{-1}=\frac{1}{n}[S][Z]_s[\bar{S}]$$

By the fundamental definition of the admittance matrix, we have:

$$[Y]_s=[Z]_s^{-1}=([S]^{-1}[Z][S])^{-1} \tag{84}$$

Now, by a fundamental theorem of matrix algebra, if A, B, and C are nonsingular matrices, then:

$$(ABC)^{-1}=C^{-1}B^{-1}A^{-1}$$

Applying this to (84), we obtain:

$$[Y]_s=[S]^{-1}[Z]^{-1}[S]^{-1} \tag{85}$$

But $[Z]^{-1}=[Y]$, hence:

$$[Y]_s=[S]^{-1}[Y][S]=\frac{1}{n}[\bar{S}][Y][S] \tag{86}$$

and we have the reciprocal relation:

$$[Y]=[S][Y]_s[S]^{-1}=\frac{1}{n}[S][Y]_s[\bar{S}] \tag{87}$$

We see from this that the symmetrical component impedance and admittance matrices are derived from the ordinary impedance and admittance matrices by similarity transformations.

Transformation of the Vector Volt-Ampere Input

The vector volt-ampere input P in terms of the original voltages and currents of the system is defined by the equation:

$$P=[I]'[\bar{E}] \tag{88}$$

Now by (75) and (76), this transforms into:

$$P=([S][I]_s)'[\bar{S}][\bar{E}]_s \tag{89}$$

But $([S][I]_s)' = [I]_s'[S]'$ by a fundamental theorem.

Hence:

$$P = [I]_s'[S]'[\bar{S}][\bar{E}]_s \tag{90}$$

Now $[\bar{S}] = n[S]^{-1}$, $[S]' = [S]$, hence:

$$P = [I]_s'[S]n[S]^{-1}[\bar{E}]_s = n[I]_s'[\bar{E}]_s \tag{91}$$

But by definition, the vector volt-ampere input in the symmetrical component quantities is:

$$P_s = [I]_s'[\bar{E}]_s \tag{92}$$

hence:

$$P = nP_s \tag{93}$$

And we see that the actual vector volt-ampere input to the system is n times the amount as calculated by (92) where n is the order of the phase of the system.

VII. Symmetrical Components in General Wye-Wye Circuit

If we write (45) in terms of complex voltages, impedances, and current, we have:

$$[E]_s = [Z]_s[I]_n + [Z]_L[I]_n + [Z]_r[I]_n + [E]_r \tag{94}$$

Let us multiply this equation by $[S]^{-1}$, we then obtain:

$$[S]^{-1}[E]_s = [S]^{-1}[Z]_s[S][S]^{-1}[I]_n + [S]^{-1}[Z]_L[S][S]^{-1}[I]_n + [S]^{-1}[Z]_r[S][S]^{-1}[I]_n + [S]^{-1}[E]_r \tag{95}$$

If we now introduce:

$[S]^{-1}[E]_s = [E]_{ss}$ the symmetrical component matrix of sending-end voltages (96)

$[S]^{-1}[E]_r = [E]_{rs}$ the symmetrical component matrix of receiving-end voltages (97)

$[I]_{ns} = [S]^{-1}[I]_n$ a matrix whose elements are the symmetrical components of line currents (98)

$[Z]_{ss} = [S]^{-1}[Z]_s[S]$ the symmetrical component matrix of sending-end impedances (99)

$[Z]_{Ls} = [S]^{-1}[Z]_L[S]$ the symmetrical component matrix of line impedances (100)

$[Z]_{rs} = [S]^{-1}[Z]_r[S]$ the symmetrical component matrix of receiving-end impedances (101)

then (95) becomes:

$$[E]_{ss} = [Z]_{ss}[I]_{ns} + [Z]_{Ls}[i]_{ns} = [Z]_{rs}[I]_{ns} + [E]_{rs} \tag{102}$$

and we have explicitly:

$$[I]_{ns} = ([Z]_{ss} + [Z]_{Ls} + [Z]_{rs})^{-1}([E]_{ss} - [E]_{rs}) \tag{103}$$

an equation for the determination of the symmetrical components of line currents. It may be noted that in case the generator and receiver voltages are balanced, a considerable simplification will be effected.

The currents in the various parts of the system are given by:

$$[I] = [A][I]_n \tag{28}$$

If we multipy this equation by $[S]^{-1}$, we obtain:

$$[S]^{-1}[I] = [S]^{-1}[A][S][S]^{-1}[I]_n \tag{104}$$

If we place:

$[I]_s = [S]^{-1}[I]$ the symmetrical component matrix of the currents in the various parts of the system (105)

$[A]_s = [S]^{-1}[A][S]$ the symmetrical component transformation matrix (106)

then (104) may be written in the form:

$$[I]_s = [A]_s[I]_{ns} \tag{107}$$

and we see that the symmetrical component matrix of the currents in the various parts of the system are obtained from the symmetrical component matrix of the line currents by means of a transformation matrix $[A]_s$, obtained from the ordinary transformation matrix $[A]$ by means of a similarity transformation.

VIII. Conclusion

The simplicity by means of which general expressions for complex networks are obtained by the use of matrix notation and transformation theory is apparent from the above examples. The systematization made possible by concise matrix manipulation makes the algebraic work a minimum and the trend of the argument is brought clearly into the foreground.

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Discussion

Myril B. Reed (Armour Institute of Technology, Chicago, Ill.): The concept of an *old* space, or mesh system, in which a network may be represented in a so-called generalized form, and from which, by means of a transformation matrix, the generalized impedance matrix may be transformed into the impedance matrix of the connected, or *new* space, network has been developed and used as the basis of the extensive work on static networks and machines written by Kron. Pipes has used this same concept.

In writing the introductory work preliminary to the application of tensors, the transformation from one space to another is not only pertinent but essential, since tensor analysis is based on transforming from one space to another. Even so, it should be pointed out that insofar as static networks are concerned the tensor concept and, therefore, transformation from an old to a new space is not necessary. In fact the C matrix of Kron and the A matrix of Pipes are somewhat artificial when applied to static-network theory. These transformations are used to establish the impedance matrix for the physical network. But this may be done rather easily by means of Kirchhoff's voltage equations in terms of Maxwell's cyclic currents, and the *old* and *new* spaces, or mesh systems, do not make the impedance matrix easier to form, understand, or use.

However, the idea of matrix transformations is useful, and can be used effectively in many ways as the papers indicated in the bibliography of Pipes' paper demonstrate. The pure mathematician has developed an extensive theory of matrices and matrix transformations which may be borrowed whole-cloth as it were, and applied to the manipulation of the set of linear equations expressing the properties of an electric circuit; and from these manipulations we may expect to reach conclusions formerly hidden by the very fact that the Kirchhoff equations are many, and, therefore, difficult to manipulate as a unit.

Louis A. Pipes: Professor Reed, in his discussion, points out that the transformation concept is used to establish the impedance matrix of the physical network and that this may be done more easily by means of a direct application of Kirchhoff's equations. For simple systems involving only a few mutual coupling coefficients, this is perhaps true. However, in complex systems, there is a very great danger that in setting up the Kirchhoff equations certain terms may be omitted because of the complexity of the problem. Once the generalized impedance matrix is written down, however, the actual impedance matrix of the system may be easily obtained without further thought on the part of the analyst by means of the "constraint" matrix, A. The philosophy of the method is very similar to the use of the Lagrangian equations in dynamics to obtain the equations of motion of dynamical systems when the energy and dissipation functions are known.

That the concept of matrix transformation is useful in electrical circuit theory has by now been amply demonstrated by the numerous papers on its application to this field which have appeared recently.

Transactions

Preprint of Papers and Discussions Comprising Pages 129-92 of the 1940 Volume

Radio-Frequency High-Voltage Phenomena

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DURING the many years that large amounts of power have been transmitted over long power lines at high voltage, an enormous amount of work has been done on research and development in connection with the high-voltage low-frequency phenomena encountered. In the years that followed, the use of low radio frequencies for communication purposes brought about the need for knowledge of high-voltage phenomena in the region of 100 kilocycles and up to about 200 kilowatts. The men associated with this equipment did a remarkably good job of design on their equipment as may be seen in some of the apparatus still in use, especially in regard to the large antenna insulators used on the long-wave antennas.

When vacuum tubes made the generation of much higher radio frequencies possible, and it was found that the shorter waves transmitted intelligence more efficiently over long distances, the use of large amounts of power for radio transmitters was discontinued, first, because there was no equipment available to produce so much power and, second, because the more efficient propagation of the shorter waves and the more efficient vacuum-tube receiving equipment provided a satisfactory means of communication with lower power. This being the case, very high voltages at radio frequencies faded into the background.

With the progression of the art, equipment capable of handling larger and larger amounts of power up to the ultrahigh radio frequencies has been developed in order to provide an ever better means of communication between the remotest parts of the globe. With the increasing power has come the problem of voltage stress but only in proportion to about the square root of the energy used, hence the high-voltage difficulties have lagged the development considerably until recently. Voltages presently in use in high-powered transmitters are sufficient to cause frequent dielectric breakdowns, but in most cases the problems have been side-stepped by overdesigning, or what was thought to be so, in order that concentrated effort could be put on other more pressing problems and also because there were apparently no tools for accurate measurement of the quantities involved.

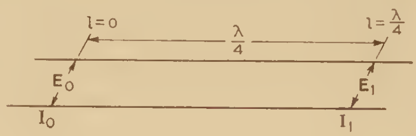
Since the advent of high-power high-frequency transmitters and of simultaneous operation of antennas on several frequencies, the issue of high-voltage radio-frequency phenomena has again come to the foreground. Voltages well over 50,000 root-mean-square volts have been developed in coupled sections[1] under test conditions and in the near future probably several times these values will be common. With the issue of insulation coming to the foreground, a simple and accurate method for high-voltage measurements seems to be a necessity. The basis of such a method has been with the electrical art ever since the development of accurate transmission line equations, the principle of the method lying in the relation between voltage and current separated by a quarter wave length of transmission line. The relation is simply that the voltage on the line at any point is equal to the surge impedance times the current at a point exactly one quarter wave length distant, either toward the receiving or transmitting end assuming no line losses. This relation holds regardless of the line terminations, the only requisite being that the surge impedance of the line over the quarter-wave region be constant.

The relation referred to was described by Steinmetz in 1908 in his "Transient Electric Phenomena and Oscillations". Steinmetz's derivation follows:

Given the general transmission line equations[2]

$$\boldsymbol{I} = A_1\epsilon^{+\alpha l}(\cos\beta l + j\sin\beta l) - A_2\epsilon^{-\alpha l}(\cos\beta l - j\sin\beta l)$$

$$\boldsymbol{E} = \sqrt{\frac{Z}{Y}}\,[A_1\epsilon^{+\alpha l}(\cos\beta l + j\sin\beta l) + A_2\epsilon^{-\alpha l}(\cos\beta l - j\sin\beta l)]$$



For simplification we can assume line losses to be zero and also let $\boldsymbol{E}_0$ be voltage at $l = 0$, the reference point on the line. The $\sqrt{Z/Y}$ becomes $\sqrt{L/C} = z_0$ commonly known as the surge impedance. At the reference point

$$\boldsymbol{I}_0 = (A_1 - A_2)$$

$$\boldsymbol{E}_0 = z_0(A_1 + A_2)$$

At a point $\lambda/4$ distant, $\beta l = \pi/2$ at which point $\boldsymbol{I}_1$ and $\boldsymbol{E}_1$ shall represent the current and voltage

$$\boldsymbol{I}_1 = -j(A_1 + A_2)$$

$$\boldsymbol{E}_1 = -jz_0(A_1 - A_2)$$

From which it follows that

$$\boldsymbol{E}_0 = -jz_0\boldsymbol{I}_1$$

which reduces to $E_0 = z_0I_1$ when only absolute magnitudes are considered. This simple derivation turns the quarter-wave line into a radio-frequency voltmeter.

Since z_0 occurring in the above relation is usually of the order of 600 ohms, it follows that high voltages and high currents go together. Both may be produced very simply by means of the arrangement shown in figure 1, in which a quarter wave length of line is suspended below an energized transmission line, one end of the quarter-wave line being closed by an adjustable short-circuiting bar. If the section is very loosely coupled to the line, that is, hung a foot or two below the line, the current in the short circuit will be found to be very large since there is only a small amount of resistance present to

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1. For all numbered references, see list at end of paper.

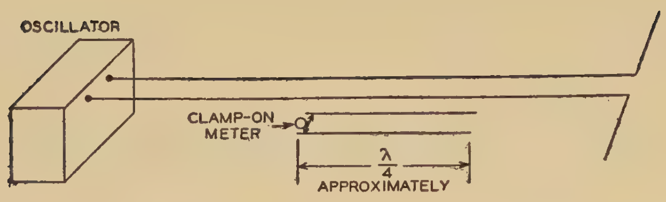


Figure 1. Quarter-wave coupled section on radio-frequency transmission line

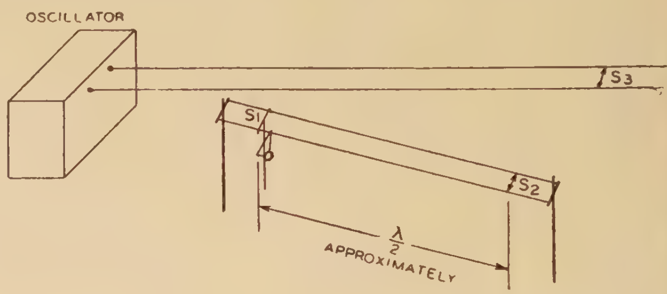
stop the flow. As pointed out above, the voltage at the open end of the section, being one quarter wave length away from the large current, will also be large and will be the absolute value of the product of the current by the surge impedance of the section.

Experience has shown that this particular arrangement led to trouble due to the difficulty of insulating the open end of the section. This was eliminated by a much more satisfactory arrangement, shown in figure 2*A*, in which a half-wave section of transmission line short-circuited at both ends and suspended in a plane not parallel to the plane of the energized transmission line is resonated to the frequency on the line by moving one or both of the short-circuiting bars until maximum current flows in the section. An arrangement of this sort may be provided with supports near or beyond the short circuit where the voltage is low, thus presenting no support insulation difficulties. Such a half-wave section may be made, for example, of number 6 copper wire with the upper short-circuiting bar fixed for current measurement and the lower one adjustable for tuning the section, being that the lower short circuit is easily accessible. The current in the fixed short circuit may be measured by a clamp-on meter or much more conveniently by an inductively coupled meter which will be referred to as a "shortometer" and is shown in figure 3. The calibration and theory of this instrument is described in appendix *A*, but it is to be noted here that such a meter reads root-mean-square values, hence all currents or voltages referred to in the following will be root mean square or effective in magnitude.

The power which is required for producing high voltages up to 60,000 volts is very moderate, being of the order of ten kilowatts. The loop resistance of the half-wave section at frequencies of the order of 13 megacycles is around one ohm with number 6 copper wire, so that if all of the line power is diverted into the section, the current developed in the short circuit is approximately equal to the square root of the power in watts, so when the section is dissipating 10,000 watts, the current in the short circuit would be about 100 amperes. With wires of the section spaced 12 inches apart, the surge impedance is 600 ohms, thus the voltage in the center of the half-wave section is about $600 \times 100 = 60{,}000$ volts, which, as a matter of fact, is somewhat higher than the arcing voltage of the clean number 6 wires spaced 12 inches apart. When higher voltages are desired, it is necessary to make the half-wave section of larger diameter wire or of tubing.

The best position of short circuit S_3 in figure 2*A* depends on the geometrical configuration of the transmission line and the half-wave section. When the short circuit S_1 of the section is about a foot below the line and the section is inclined at about 15 degrees, it is possible to find a position of short circuit S_3 which, when the half-wave section is nearly in tune, reduces the standing waves along the transmission line to reasonable proportions so that the transmitter is able to deliver power. The best position of this short circuit depends on how much additional resistance is introduced into the section by, say, a sample insulator under test placed across the section. Thus short circuit S_3 is made readily adjustable. This short circuit is then used as a kind of mutual-coupling control or adjustable transformer ratio.

Figure 2A. Half-wave coupled section to transmission line



High-Voltage Phenomena

The first phenomenon usually encountered with the half-wave section as the movable short circuit approaches the resonant point and the current increases to 25 or 30 amperes is that a flame somewhat similar to a Bunsen-burner flame and about six to eight inches long shoots into space from some point near the middle of the section. Such flames are usually directed upward and blow very easily in the wind to a point of low voltage where they go out. Immediately another flame spurts out from near the center of the section and repeats the process. If the section has considerable slant with respect to the ground, the flames will usually run up the wire even if there is no wind blowing and will go to the low-voltage point unless they strike a projection or sharp point where they will stop moving and will maintain themselves until the power is dropped or the section is detuned. If the wire of the section has a coating of corrosion from the weather, the voltage which the section can stand may be as low as 15,000 or 20,000 volts. This voltage can be doubled or raised even higher before an arc is produced if the wire is made clean and bright by sanding and wiping with a cloth. It is also interesting to note at this point that if the short circuits are taken off and a 60-cycle voltage is applied across the section, the region which has been cleaned shows no corona, while the parts remaining dirty glow with intense and spotty corona.

It is of particular importance to note the striking contrast that exists between 60-cycle phenomenon and 13,000-kilocycle phenomenon in regard to the mechanics of the voltage breakdown of the wires. At 60 cycles as the voltage is gradually increased, first a very faint corona glow develops. As the voltage rises and the corona becomes more intense, streamers shoot out from the wires and finally they become long enough to bridge the gap between the wires terminating in complete breakdown or arc-over. This process is seen to progress in a more or less continuous manner from no

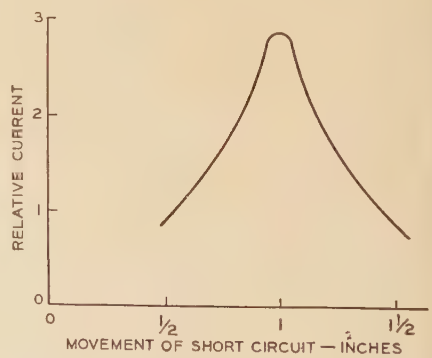


Figure 2B. Approximate half-wave-section tuning response when made of number 6 copper wires spaced 12 inches apart

indication of voltage through gradual steps to complete arc-over between wires. Such is not the case at 13,000 kilocycles. When the voltage on the section is gradually raised, there is no indication of increasing voltage stress preceding the arc into space. As soon as the voltage gets up to a certain critical value, an arc occurs not between wires, but suddenly shoots into space just as if the whole voltage had been instantly applied, there being no noise and no sign of corona accompanying the gradual rise in voltage.

The voltage that a given wire will take at 13,000 kilocycles under the same clean surface conditions varies considerably from day to day apparently depending on atmospheric conditions. Occasionally sections made of clean, smooth number 6 wires spaced 12 inches apart will stand as much as 45,000 volts under the best of atmospheric conditions. One of the strangest phenomena of all is the action of smoke from rubbish or grass fires. Wherever the smoke strikes a high-voltage region of the section, a jagged, crackling spark shoots out, and if the smoke distribution is uniform, the voltage rating of the section will sometimes drop to as low as 20 per cent of the normal rating depending on the concentration of smoke.

The electrostatic field near the midpoint of the half-wave section when a large current is flowing in the short circuits is quite extensive and produces some curious effects, for example, considerable diathermy effect can be felt in one's legs when standing at least four or five feet away. The magnetic field about the short circuit also produces some curious phenomena. If a piece of number 6 wire is fastened onto a wooden handle with iron nails bent around the wire to provide an adjustable short circuit, the nails get red hot while the current in the wire is sufficient to raise the temperature of the latter only a little above atmospheric.

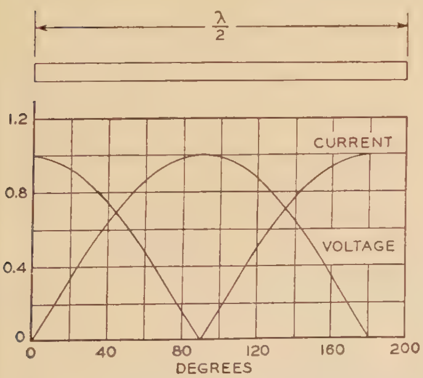


Figure 2C. Current and voltage distribution over a half-wave coupled section

High-Voltage Measurements

The voltage which occurs between the conductors of the half-wave section may be applied across what may be termed "samples under test" such as needle gaps, sphere gaps, insulators, capacitors, etc. These samples are fastened to sections at a distance of one-quarter wave length from the fixed short circuit in which the current is observed. Due to the capacity of the sample the movable short circuit has to be translated toward the fixed short circuit in order that the section may be resonated. The distance through which this short circuit is moved is a very accurate measure of the capacity of the sample and may be used for ascertaining the capacity of the latter. See appendix *B*.

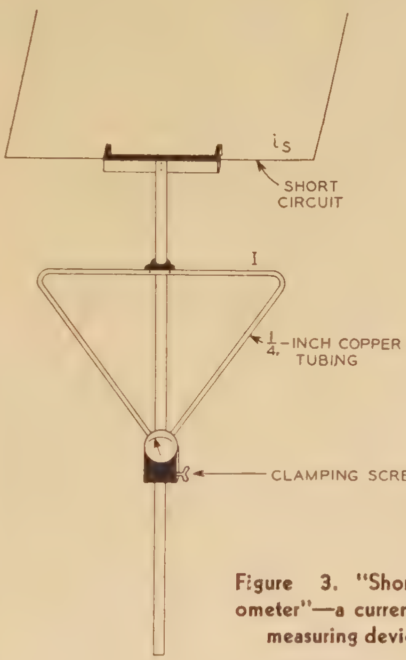


Figure 3. "Shortometer"—a current-measuring device

In order to visualize the more fundamental features of the high-frequency high-voltage phenomena involved, the following arrangements well known to the 60-cycle technique were investigated.

Needle Gaps

In the case of needle gaps the action at 13,000 kilocycles is quite different from that at 60 cycles. Figure 4 shows a curve of the very faintest sign of corona glow with points at 60 cycles in a dark room. On the same sheet are also plotted the voltages at which breakdown occurs at 13,000 kilocycles. In the latter case there is no sign of corona before brilliant white spots, or what may be more descriptively named points fire, suddenly develop at the sharp tips as soon as the gradually rising voltage reaches a certain critical value. Considerable energy is immediately dissipated at the points as indicated by the fact that tips are dulled each time a breakdown occurs and also by the fact that the section current drops immediately, showing that a loss or resistance has been introduced into the section. Due to the melting of the points, they can be used only once, after which they have to be sanded, and even then, with the most careful precautions the results are far from being exactly reproducible as shown by the dispersion of points.

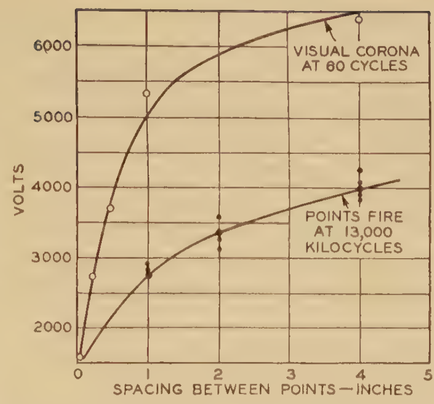


Figure 4. Behavior of needle gaps at 13,000 kilocycles and at 60 cycles

Wire Gaps or Parallel Wires

Figure 5 shows the breakdown voltages between wires of various sizes at close spacings in a configuration as shown at the top of the curve sheet. Here again no corona is seen and also no agreement is found between the shape of these curves representing arcing voltage at 13,000 kilocycles and the 60-cycle spark-over voltage as shown in figures 50, 51, and 93 in Peek Jr.'s "Dielectric Phenomena in High Voltage Engineering". However, it is of considerable interest to note that the shape of the 60-cycle corona curves in the same figures is somewhat similar to the curves of figure 5.

Sphere Gaps

Figure 6 shows a curve taken with two-inch spheres set at various spacings. Here for the first time the agreement between 60-cycle spark-over data and 13,000-kilocycle arc-over data is surprisingly good, showing that sphere gaps hold as standards for high-voltage measurements at least up to 13,000 kilocycles when the spacing between the spheres is considerably less than their diameter. As previously there is no sign of corona. In addition the results are surprisingly reproducible.

At 60 cycles, in the case of sphere gaps, when the spacing between the spheres is considerably less than their diameter,

there is also no corona visible before spark-over. It is to be noted that the maximum gradient that exists between spheres under these conditions is almost uniform, and thus, when a disruptive gradient is reached, the whole region of maximum stress is simultaneously broken down producing the spark-over. In the case of points and parallel wires at 60 cycles, the maximum gradient is not uniform at spacings larger than the diameter of the wire but does reach a disruptive value producing corona near the conductors if the applied voltage is sufficiently high. At 13,000 kilocycles such an enormous loss apparently occurs as soon as a disruptive gradient is reached that the ionization is not partial causing corona as at 60 cycles, but is instead complete causing an arc.

This view is further borne out if we consider what Peek Jr. describes as "Disruptive Critical Voltage" and "Disruptive Critical Gradient" on page 188 of the previous citation. Here he shows that corona loss occurs below the voltage which produces visual corona, the voltage and gradient at which corona loss begins being named respectively, "Disruptive Critical Voltage" and "Disruptive Critical Gradient". If the gradients corresponding to voltage applied to the wires as shown in figure 5 are computed from the exact equation for maximum gradient and are plotted as shown in figure 7, a fairly good agreement is found to exist between the 13,000-kilocycle breakdown gradients and the 60-cycle "Disruptive Gradient" values calculated from Peek Jr.'s empirical formula for this gradient shown in table III. Thus again we see that apparently as soon as a voltage is reached which would produce a corona loss at 60 cycles, an arc is produced at 13 megacycles.

The "Disruptive Critical Gradient" theory can also be used to explain the action of needle gaps at 13 megacycles. Apparently as soon as the magnitude of the 13-megacycle voltage is equal to the 60-cycle voltage which would cause the first bit of corona loss, the loss at 13 megacycles is so large that points fire is produced, from which it follows that the curve for points fire shown in figure 4 should be below the curve for visible corona at 60 cycles, and this is the case.

It is of interest to note the ratio between the 60-cycle voltage which causes the first signs of visible corona and the 13,000-kilocycle breakdown voltage for needle gaps. In table I are given the ratios of the ordinates of the two curves in figure 4. In table II, for comparison with table I, are tabulated the ratios of 13,000-kilocycle breakdown gradients and 60-cycle visual corona gradients for parallel wires. The 13,000-kilocycle values were obtained from figure 7 while the 60-cycle gradients were computed from the empirical equations given by Peek Jr. in "Dielectric Phenomena in High Voltage Engineering".

In table III are compared the arc-over gradients for parallel wires at 13,000 kilocycles and the calculated "Disruptive Critical Gradient" as obtained from the empirical formula which was taken from page 192 of the previous citation. This tabulation shows the most striking correlation between 60-cycle and 13,000-kilocycle high-voltage phenomena because it seems to show that disruptive gradients are almost independent of frequency. It has been pointed out above that there is apparently no mild dielectric breakdown at 13,000 kilocycles preceding arc-over. Furthermore, since losses are probably proportional to the second power of the frequency, it seems likely that corona cannot exist at such frequencies as 13,000 kilocycles but that complete breakdown of the region must take place as soon as the disruptive gradient is reached.

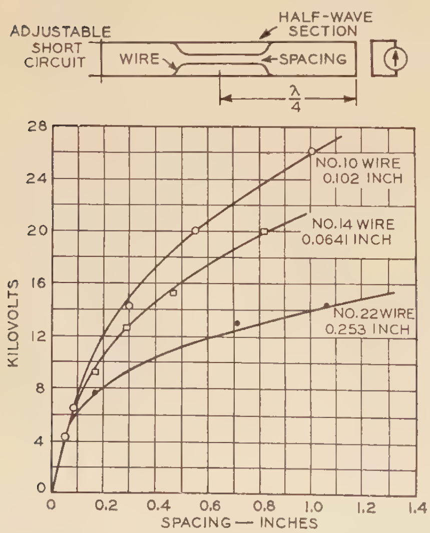


Figure 5. Breakdown tests on parallel wires at 13,000 kilocycles

Variable Air-Capacitor Voltage Ratings

In the light of the fundamental facts presented above, it is now possible to begin to understand the high-voltage high-frequency performance of many of the various pieces of equipment presently in use in modern high-powered radio transmitters, and further, since it is possible to give a reasonably correct diagnosis of the faults of the apparatus, it follows that a basis for a more correct design has also been established.

Table I

Spacing Between Points (Inches)	13,000-Kilocycle Points-Fire Voltages Taken From Figure 4 (Kilovolts)	60-Cycle Corona Voltages From Figure 4 (Kilovolts)	Ratio
0.5	2.1	3.7	0.57
1.0	2.8	5.3	0.53
4.0	4.0	6.4	0.62

Variable air capacitors in high-power transmitters are one of the pieces of equipment which are subjected to rather high radio-frequency voltages, seldom much over 6,000 volts, but nevertheless sufficiently high to produce annoying and troublesome arc-overs at frequent intervals. Whenever such difficulties developed, the usual practice seems to have been to analyze the trouble in the light of 60-cycle phenomena. For example, it seems to be quite common for manufacturers to list the voltage ratings of variable air capacitors as straight-line functions of the plate spacings both at 60 cycles and at high radio frequencies. The radio-frequency ratings given are somewhat lower than the 60-cycle ratings. In

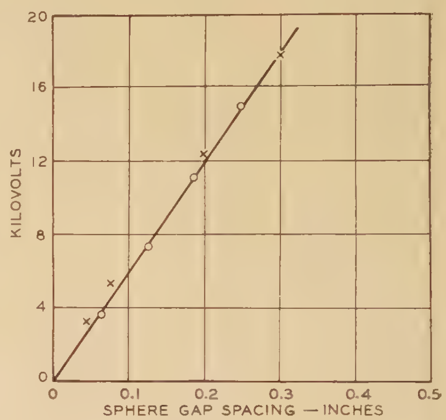


Figure 6. Comparison of sphere-gap performance at 60 cycles and at radio frequencies

Circles—13,000 kilocycles, 2-inch spheres

Crosses—60 cycles, $2^5/_8$-inch spheres

Table II

Wire Size	13,000-Kilocycle Arc-Over Gradient From Figure 7 (Kv per Cm)	Calculated 60-Cycle Visual Corona Gradient g_v (Kv per Cm)	Ratio
22	51.3	80.0	0.64
14	38.7	61.0	0.63
10	35.3	54.7	0.65

$$g_v = 29.8\left[1 + \frac{0.30}{\sqrt{\frac{D}{2}}}\right]$$ from Peek Jr., page 56.

addition, plate thickness is given some consideration, statements usually being made to the effect that thin plates reduce the maximum voltage ratings by a small amount. It is also sometimes mentioned that the plate shape at the edges has a somewhat marked effect on the rating, square edges tending to produce a lower spark-over voltage.

The 60-cycle ratings are usually correct. Even though the corona which develops during tests is not a straight-line function of voltage, the spark-over voltages vary almost linearly with spacing practically regardless of plate thickness or edge shape. The above data have shown that sphere-gap spark-over voltages agree almost to the point of coincidence, regardless of frequency up to 13 megacycles as shown in figure 6. Figure 4, the curve for 60-cycle corona glow and 13-megacycle points fire, tells an entirely different story. Herein lies the crux to the situation. The 13-megacycle points-fire curve is not at all linear with voltage, but is quite similar to the 60-cycle visible-corona curve for points, and, in addition, as table I shows, is only about 60 per cent of the corona-glow voltage for points.

Naturally, during the life of most capacitors, even though some attempt has been made in the better class of equipment to round off plate edges at least to a small degree, arc-overs occur, leaving small rough spots similar to points. This being the case, a capacitor in service is comprised of smooth plates with varying numbers of little rough spots due to arc-overs on the plate edges. Under these conditions, it is only reasonable to expect that the high radio-frequency voltage rating of such a piece of equipment might be similar to the voltage rating of needle gaps at the same spacing and at the same frequency. When the capacitors are new and reasonably smooth surfaces prevail throughout, it is possible that the voltage rating might follow along the lines of parallel wires which have diameters equal to plate thicknesses since the present common designs simulate a mesh of parallel wires at the plate edges, especially when the plates are in the position of maximum capacity.

Figure 8 gives a rather complete picture of the performance of a number of commercial capacitors after they had been in service for a considerable period of time. Here it is seen that the 60-cycle rating is linear with spacing as claimed by the manufacturers and that voltages well over what might be expected in the highest-powered transmitters can be applied across the capacitor terminals if the frequency of the voltage is in the 60-cycle region. The 13-megacycle high-voltage tests show an entirely different relation between spark-over voltage and plate spacing, the spark-over voltages being much lower than the 60-cycle spark-over ratings, thus explaining the unsatisfactory operation of many supposedly well-designed capacitors.

As is well-known to the 60-cycle technique and as has been pointed out above for 13 megacycles, needle gaps are rather unsatisfactory for voltage measurement compared with sphere gaps since the spark-over voltages are not exactly reproducible, but are more or less dependent on the laws of probability. Since it was pointed out that the capacitors under test were spotted with arc-over marks, it follows that their voltage ratings both at 60 cycles and 13 megacycles should depend to a certain extent on probability, as do needle gaps, hence an exact rating cannot be given, the wide dispersion of points defining regions of limits within which spark-overs will probably occur at various spacings. It is further to be noted on figure 8 that the capacitors tested apparently presented shapes more similar to points than to parallel wires since it is seen that the arc-over voltages for parallel wires having diameters about equal to the plate thicknesses of the capacitors tested were considerably higher.

At present, and at least until further investigation proves otherwise, it seems possible that the high radio-frequency voltage ratings of a variable air capacitor might be obtained from 60-cycle tests.

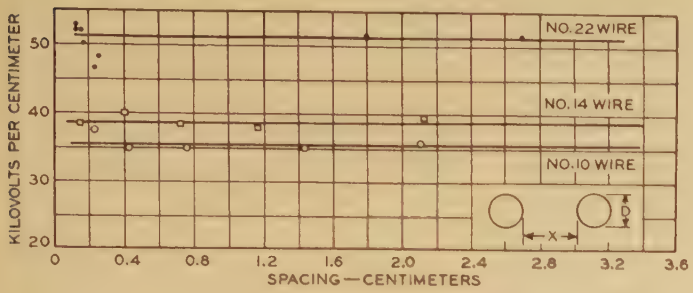


Figure 7 (above). Spark-over gradients for wires at 13,000 kilocycles

Maximum gradient

$g = \frac{e}{x} W$ where

$$W = \frac{\frac{x}{D}\sqrt{1+\frac{2D}{x}}}{\cosh^{-1}\left(\frac{x}{D}+1\right)}$$

and e = applied voltage

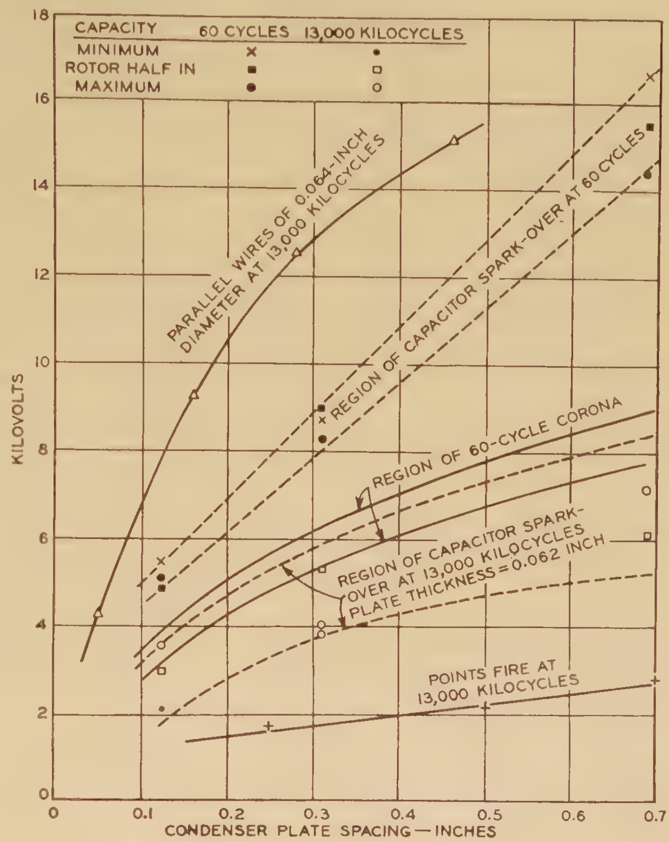


Figure 8. Spark-over voltages of variable air capacitors at 60 cycles and at 13,000 kilocycles

Table III

Wire Size	13,000-Kilocycle Arc-Over Gradients From Figure 7 (Kv per Cm)	Calculated 60-Cycle "Disruptive Critical Gradient" g_d (Kv per Cm)	Ratio
22	51.3	70.7	1.38
14	38.7	41.0	1.06
10	35.8	34.8	0.99

$$g_d = 29.8\left[1+\frac{0.30}{\sqrt{\frac{D}{2}}}\,\frac{1}{\left(1+230\left(\frac{D}{2}\right)^2\right)}\right]$$ from Peek Jr., page 192.

Previously the 60-cycle spark-over ratings have apparently proved to be much in error at high radio frequencies so an entirely different method will have to be used if the same errors are to be avoided. Tables I and II show that the points fire voltages and the arc-over voltages for needle gaps and wires are about 60 per

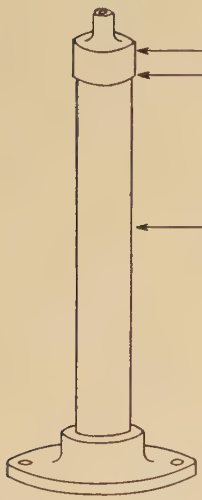


Figure 9. Radio-frequency pedestal insulator

cent of the 60-cycle visual corona voltages for the same test specimens. Figure 8 has shown that variable air capacitors having a given spacing between plates have ratings in the region between such test specimens as needle points and parallel wires, so it is reasonable to believe that a similar fraction of the 60-cycle corona voltage might be taken as the maximum radio-frequency rating of a capacitor. Figure 8 also shows a region for the first signs of 60-cycle visual corona on the group of capacitors used in the tests. However, probably due to irreproducibility of such things as corona glow and needle gap spark-over voltages, the 13-megacycle spark-over voltages are seen to be a little more than 60 per cent of the corona-glow voltages. Where corona first appears on the plates at 60 cycles is not necessarily the point where the 13-megacycle spark-over will occur; nevertheless, the points of 60-cycle and 13-megacycle spark-overs usually coincide, thus substantiating at least a part of the older test methods.

The insulating material used to separate one set of plates from the other in a variable air capacitor provides one point of difference between an exact similarity of capacitors to needle gaps and parallel wires, and therein lies a possible source of error to be carefully avoided. At 60 cycles corona usually develops at the point of contact of the metal plates with this insulating material, the voltage at which this occurs usually having little bearing on the radio-frequency voltage rating. The corona to be observed to obtain the radio-frequency voltage rating is that from the edges of the plates into air.

In the above discussion and presentation of curves it has been pointed out that the radio-frequency voltage rating for sphere gaps and needle points at the same spacing are quite different, the latter being very much lower; the difference being due to the field configurations produced by each set of electrodes. In the case of spheres when the spacing between them is small compared to their diameters, the maximum field or gradient has been shown to be almost uniform, requiring a high voltage with respect to sphere separation to bring the region of maximum stress to the breakdown value. In the case of needle gaps there is no region of uniform stress at reasonable spacings, hence high breakdown gradients are produced at low voltages. It is clear that the radius of curvature of the sphere has all to do with the production of the desired uniform field, hence it is evident that the ultimate goal in capacitor design is the production of uniform fields at regions of maximum stress, which simply means maximum radii of curvature of plate edges rather than increased spacings.

Figure 8 shows that a large improvement could have been made in the capacitors under test if all gradients had been kept as good as that between wires having diameters equal to plate thicknesses. However, it is requisite to use radii of curvatures on the plate edges which are at least one order of magnitude higher than the dimensions of the spots produced by arc-overs, with the hope that the comparatively gradually curving surfaces will partially shield the rough spots produced. The reproducibility of sphere-gap spark-over voltages after repeated spark-overs has proved the validity of such a shielding effect. Not only do the plate edges need larger radii of curvature to reduce high gradients, but also all parts of the apparatus including such things as frame work which are at a high potential with respect to ground or with respect to any object in the near vicinity, if the ultimate in performance is to be achieved.

Insulator Tests

It seems to be common practice at present when manufacturing standoff and strain insulators, to make an abrupt joint between the metal collars and the insulating material as shown in figure 9. If 60-cycle voltages were applied across such insulators, the spark-over voltages would increase almost in proportion to the length of the insulating material. At high radio frequency this is not at all the case, and, in fact, the length has only a small bearing on the matter, the actual rating of the insulator being dependent on such things as the radius of curvature of the cap at the place where it meets the insulating material. As a rule, with insulators of this construction, the material of which the insulator is made is many times better than it need be because it is not the material but the air which breaks down. The damage which occurs is usually not due to the failure of the material under stress, but merely due to local heat produced by the arc which starts from one of the caps. In order to develop the full strength of the insulating material in practice as well as in test, it is necessary to provide the insulator with some sort of corona shields very familiar to the 60-cycle practice, but at high radio frequencies these corona shields have to be considerably better than they need be at 60 cycles. What is necessary at these frequencies is a corona shield which at 60 cycles would produce spark-over before corona, that is, an almost uniform gradient. Anything short of that results in

Figure 10. Radio-frequency strain insulator

lower radio-frequency spark-over than at 60 cycles. This point is difficult to overemphasize. If for the sake of illustration we assume an insulator has been provided with shields and that during a 60-cycle test there developed corona at a sharp point along the wires leading to the insulator, perhaps three feet away from opposite terminals, it is safe to predict that at high radio frequencies a breakdown will take place at the previous corona point, and this may happen in spite of the fact that the spacing between the corona shields may be only one-half inch. In order to emphasize this point still further, it might be well to point out the effect of a sharp point in some apparatus of a common type. Quite frequently rectangular strain insulators similar to the one shown in figure 10 are used as part of antenna equipment. These insulators have shackles and pins as fastening members, the pins being provided with cotter pins to insure the permanency of the arrangement. When used in the normal way, the voltage rating at 13 megacycles is only about 18,000 volts because the sharp points of the cotter pins produce arcs into space. If the cotter pins are removed the voltage can be in-

creased to over 40,000 volts and still nothing happens.

In testing insulators it is well to keep in mind that so-called insulator failures occur for two entirely different reasons; (1) breakdown of the air around the metal fittings where the metal comes in contact with the insulating material; (2) breakdown of the insulating material itself. Most of the insulators in use at the present time fail for the first reason. Only a few equipped with carefully designed corona shields or means for distributing the gradient equally over the length of the insulator breakdown for the second reason. The only exception to the latter case consists of insulators of the standoff type which are provided with metal screws that go a long way into the insulating material, thus producing an enormous concentration of flux in the material.

Insulating materials such as synthetic resins prove to be unsatisfactory at high-radio-frequency high voltages. When 1,000 or 2,000 volts at 13 megacycles is applied across a strip of such material about two inches long, charring streamers start over the surface of the specimen, accompanied by considerable smoke, and as soon as the streamers from opposite sides meet, a short circuit is produced and the test is over.

Conclusion

The results of the above measurements seem to indicate rather definitely that there exists a striking correlation between high-voltage phenomena at high radio frequencies and at 60 cycles. The 60-cycle phenomenon which parallels the high-frequency breakdown most closely seems to be the 60-cycle corona. The gradients at which high-frequency breakdown occurs appear to follow the same laws which are followed by the 60-cycle corona. The values of the gradients at which high-frequency breakdowns take place appear to be systematically equal to about 60 per cent of the gradients at which the 60-cycle visual corona begins and, moreover, appear to be equal at least approximately, to the 60-cycle so-called "Disruptive Gradient", that is, those gradients at which corona losses begin to occur at 60 cycles. Our measurements are too meager to establish the extent and the degree of this correspondence between the 60-cycle disruptive gradient and the high-frequency breakdown gradients. These measurements, however, appear to be sufficiently consistent and appear to cover a sufficient variety of electrode configurations to make it seem very probable that such a one-to-one correspondence does exist. If this is the case, and we believe it is, it is not unreasonable to suppose that in the not too distant future, it will be possible to derive useful 60-cycle information from high-frequency measurements. It is only a matter of minutes to determine the breakdown voltage, and hence, the breakdown gradients between two wires or cables at a high radio frequency. If this breakdown gradient so determined is also the disruptive gradient at 60 cycles and will vary with temperature, humidity, smoke, dust, and other conditions in exactly the same way that the 60-cycle disruptive gradient does, then it would be possible with a relatively simple high-frequency setup to find out what a proposed 60-cycle arrangement will do under given conditions. If the 60-cycle disruptive gradient is really equal to the high-frequency breakdown gradient at all, it is difficult to see why the two gradients would behave differently under varied conditions.

In conclusion it should be added that our experiments were made with frequencies all lying in a relatively narrow band around 13,000 kilocycles. Somewhere below this band there lies a transition region in which corona ceases to exist. Our experiments were made primarily for the purpose of answering certain concrete questions in regard to a particular insulation problem and proper facilities were not readily available for extending this investigation into other frequency regions to make it more inclusive.

Appendix A

Upon the first impression it might be thought that the "shortometer", the much-used current-measuring instrument in all of these tests, would not be independent of frequency, but such is not the case as has been found by experience and may be easily proved as follows:

The current I, in the shortometer, as shown in figure 3, is dependent upon the voltage, E, induced in the loop of the instrument and inversely proportional to the reactance, ωL, of the loop. At the high radio frequencies at which the instrument is used, the impedance is of a higher order of magnitude than the resistance, hence the latter may be neglected. The voltage induced in the instrument loop is equal to the product of the mutual impedance between the loop and the short circuit, times the current, i_s, in the short circuit.

$$I=\frac{\omega M i_s}{\omega L}=\frac{M i_s}{L}$$

in which ω is equal to $2\pi f$ and M is the mutual inductance between the shortometer and the short circuit. Thus, it would seem that the shortometer current is independent of frequency so long as the above quantities predominate.

The accuracy of this whole method is seen to depend entirely upon how accurately the currents involved can be measured. At such high frequencies there is always considerable doubt as to the accuracy of the ammeters used, and, in fact, many of the instrument companies furnish a correction chart for their instruments when used at frequencies above one megacycle. In view of this fact, a calorimetric method was used to standardize two clamp-on meters as shown in figure 11.

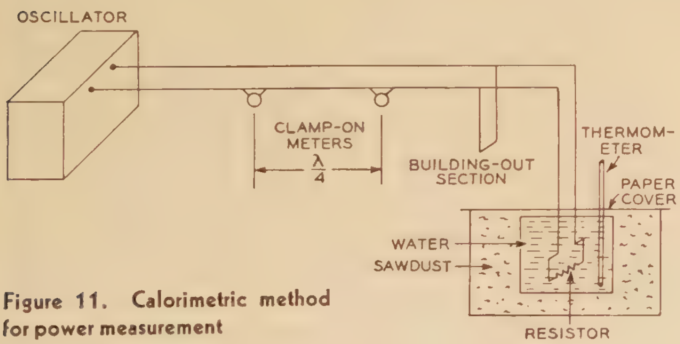


Figure 11. Calorimetric method for power measurement

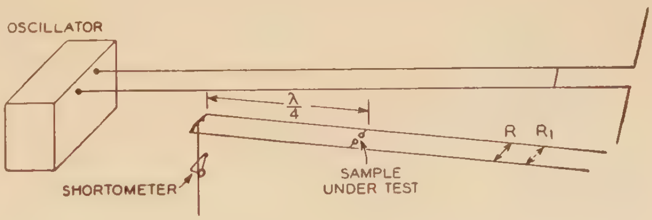


Figure 12. Test setup

The theory of the standardization is as follows:

The line from the transmitter to the dissipating resistor immersed in the water was very carefully balanced so that all of the energy on the line was series current which simply means that the ammeters would read the same regardless of on which side of the line they were placed. This eliminated any possibility of using the transmission line as a single conductor and the resistor as a capacitive by-pass to the line image in the ground. The resistor did

not match the surge impedance of the line, hence, a building-out section was installed in order to make a good balance on the line at the transmitter possible.

The conversion of electrical energy into heat at a known rate in the calorimeter is an accurate and fundamental measure of the power being transmitted by the line. The product of the readings of the clamp-on meters, spaced one-quarter wave apart, when multiplied by the surge impedance of the line is a measure of power also, and this quantity equated to the power delivered to the calorimeter gives a standardization of the meters.

In this particular case the calorimeter and its contents had a heat capacity of 12,700 calories per degree centigrade as measured by weighing the various constituents which absorbed heat and also taking into account their specific heats. The temperature rise as noted over a ten minute period by a very accurate thermometer was 19 degrees centigrade or 1.9 degrees centigrade in one minute. This gave a value of $1.9 \times 12{,}700/60 = 403$ calories per second which is equal to 1,690 watts when multiplied by 4.185, the conversion factor for heat into work. The line ammeters read 0.77 and 1.00, hence $600 \times 0.77K \times 1.00K = 1{,}690$, $K = 1.915$, where K is the multiplying factor for the meter in order to convert its readings into amperes.

When the standardized ammeter and the shortometer are put on a short circuit at the same time and current is caused to flow in the section, the reading of the shortometer may be adjusted to any desired value by simply moving the instrument up or down the staff after loosening the clamping screw. In this way positions of the instrument on the staff may be marked so that the dial of the shortometer will read directly in amperes as shown by the clamp-on meter, taking its correction factor, K, into consideration. From the above shortometer equation it is seen that if the mutual inductance, M, between the shortometer coil and the short circuit is decreased, the shortometer current, I, will be proportionately less for the same short-circuit current, i_s. Being that short-circuit currents of the order of 100 amperes or more have to be measured, the shortometer can be given a convenient multiplying factor by decreasing M, which simply means moving the instrument down its staff.

When dealing with currents too large to be measured by the clamp-on meters at hand, the shortometer may be further calibrated against itself. For instance, the section current may be adjusted to near full-scale reading for the shortometer by adjusting the transmitter output. At this time the shortometer may be moved down its staff until the original reading is cut in half or any other desired value, thus giving a multiplying factor of two or the inverse of whatever the reading was reduced to In order to make sure that the shortometer reading changed due only to the movement of the instrument on its staff, a meter may be clamped on the transmission line which usually carries a very small current compared to the section short circuit. By means of this meter and a remote control on the transmitter, the power on the transmission line may be kept constant during the shortometer calibration.

The shortometer may be similarly calibrated to read line currents by comparing it with a standardized ammeter clamped onto the line. Being that the field configuration in this latter case is different from that around a short circuit, the calibrations for measuring short-circuit current will be different from those for line currents. Also, since field configuration and dimensions determine the mutual inductance, M, between the shortometer coil and the circuit in question, the shortometer must always be used in the position in which it was calibrated and in conjunction with a short circuit of the same length as the calibrating short circuit. In other words, the shortometer staff must be provided with a calibration for each field configuration in which the instrument is going to be used.

Appendix B

When any piece of equipment is put across the mid-point of a half-wave section, the capacity which it introduces at that point detunes the section so that it is no longer resonant to the frequency on the transmission line. The section can be again made resonant by moving the adjustable short circuit from the point of original and fundamental section resonant point such as R' in figure 12 to a new location, R. From the length of line RR' the exact capacity of the test specimen can be obtained in the following way: It can be assumed that the capacitive reactance of the test specimen was equal to the capacitive reactance of a short section of open line at the center of the coupled section. Instead of cutting this equivalent length out of the center of the half-wave section in order to decrease the capacity to the original value and thus restore resonance, it is much more convenient to move the adjustable short circuit to the new position, R, the distance RR' being equal to the length of section which had to be cut from the center point.

The reactance of an open section is equal to

$$z = -jz_0 \cot 360° \frac{RR'}{\lambda}$$

or

$$\frac{1}{\omega C} = z_0 \cot 360° \frac{RR'}{\lambda}$$

when only absolute magnitudes are considered and which further reduces to

$$C = \frac{1}{z_0 2\pi f \cot 360° \dfrac{RR'}{\lambda}}$$

Appendix C

Additional Precautions

During high-voltage measurements it is very important to make certain that the radio frequency is not modulated. This is particularly true when the power of the transmitter is varied by remote control and when most of the power tubes are operated below the point of saturation. In our investigations we found it very convenient to connect the vertical plates of a cathode-ray oscillograph across a few inches of the movable short circuit of the half-wave section, while the horizontal plates were connected, as usual, to the sweep circuit. This, or an equivalent arrangement, should always be employed during such measurements to avoid possible errors which may, under some conditions, amount to some 40 per cent.

Harmonics

When a half-wave section is used in making the high-voltage measurements, the second harmonic may contribute to the current but not to the voltage. The third harmonic and other odd harmonics may contribute to both. If harmonics are suspected it is quite easy to make certain whether they are actually present. This may be done by moving the adjustable short circuit to the half-wave positions for the various harmonics and by measuring the current in the short circuit with a sensitive instrument.

In our measurements the harmonic voltages were negligible, but it is quite likely that under some conditions these voltages may affect the results and for this reason this simple check for harmonics is strongly recommended.

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1. Coupled Networks, **Andrew Alford.** IRE *Proceedings*, 1940.

2. Transient Electric Phenomena and Oscillations (a book), **Steinmetz.** Page 287, equation 17.

Discussion

E. A. Leach (nonmember; General Electric Company, West Lynn, Mass.): A brief discussion of the conclusions given in this paper is presented here to emphasize some of the valuable pointers given on insulator design, and to corroborate from independently taken measures, some of those characteristics of breakdown, on air-dielectric capacitors. Our experience with high-voltage radio-frequency insulator design has shown that the failure of an insulator could always be traced to the point where metal fittings were abruptly ended on the solid insulation. Such a condition as outlined in figure 9 of the paper is typical and the piling up of an excessive potential gradient adjacent to the juncture of metal cap and insulator will create excessive heating of the air and solid insulation at that point. By the addition of a suitable corona shield on the cap end and better yet on both ends, the safe operating voltage of a particular insulator may be improved several hundred per cent, and heating practically eliminated.

Another point that is often overlooked in insulator design is that the air film between metallic parts and a solid insulation is a bad offender. The air film, which is often only a few thousandths of an inch in thickness, may show corona breakdown at very low voltages, indicating that the gradient distribution is very poor at that point. An

easy and effective way to minimize trouble from air film breakdown is to fill the air film space with a Glyptal or other insulating varnish. By so doing, you have automatically improved gradient distribution by the simple expedient of substituting a material with a dielectric constant of 3 or 4 for the air with its K of 1. Improvement of as much as 100 per cent may result from this simple device.

The correlation between 60-cycle phenomena and phenomena at moderately high radio frequencies has been used as a basis of design work here for some time. The analysis and test data given in connection with figure 8 check comparable data accumulated here using an entirely different method of voltage measurement. On small units such as the Cardwell "midway" size and Hammarlund "*MTC*" size and on which much of our test data have been taken, we have found that the 60-cycle corona voltage point and the 60-cycle flashover point come very close together. Furthermore, we have found it satisfactory on these small units to translate our radio-frequency requirements into terms of 60-cycle flashover voltages for purposes of inspection and manufacturing test work. The advantage, of course, lies in the fact that the flashover point can be more easily checked than can the corona-formation point. On large units the spread between the 60-cycle corona point and the 60-cycle flashover point is large and on these the corona point is the determining factor from which the radio-frequency capabilities are figured.

In small units we have found that rounded plates in variable capacitors do very little good at voltages lower than 1,500 peak. Above this voltage, the rounding of plates becomes more and more important and at the same time spacing and plate thickness must be increased. For any given plate thickness there is a reasonable limit of plate spacing beyond which there is little improvement of voltage breakdown characteristics. Each type of capacitor construction seems to present slightly different breakdown characteristics; hence no one set of data will answer exactly as a design standard for all methods of construction.

Andrew Alford and Sidney Pickles: We should like to acknowedge our appreciation of E. A. Leach's discussion of our paper.

It may be of interest at this time while discussing insulators to mention very briefly some observations which we made recently at still higher frequencies, namely at 110 and 94 megacycles. At these ultrahigh frequencies such materials as the best grades of glass and ceramics are no longer excellent insulators in that there is a much greater tendency for the insulating material to heat. For this reason metal fittings play a somewhat lesser part. At these frequencies only such excellent insulating materials as quartz and paraffin behave approximately like the best ceramics at 13 megacycles. The trend toward failures on account of heating already becomes noticeable at 20 megacycles.

The breakdown of air itself seems to occur at approximately the same voltages and behaves apparently according to the same laws. Our quantitative data, however, are not as yet sufficiently complete to be presented at this time.

A New Time Standard

HENRY E. WARREN
ASSOCIATE AIEE

RESEARCH by many individuals since the beginning of the century has added two new instruments for time measurement to the generally accepted pendulum clock. All of these are based, of course, on the primary astronomical standard which involves the revolution of the earth on its axis.

The oldest of these secondary time standards, the pendulum clock, has been perfected to such an extent that in the form of the so-called Shortt free pendulum, any error can be discovered only with great difficulty. Consequently, this device has come to be over the past decade the accepted standard for certain important purposes. The time signals which are sent out for use by navigators and scientists are generally derived from free pendulum clocks maintained with utmost care in government laboratories. The time-keeping precision of these clocks is said to be of the order of one part in 30,000,000 or about a second a year.

The next most precise standard, namely, the vibrating quartz crystal which is universally used for the control of radio frequency and also for certain kinds of time service, has a precision which is said to exceed one part in 5,000,000 over a considerable period of time. However, this type of standard, if used for the measurement of time as distinguished from radio frequency, is very expensive and complicated and requires expert supervision. As many as ten or more vacuum tubes are needed to reduce the frequency of the quartz crystal to the standard 50 or 60 cycles of our power systems. Obviously, continuity of service with such a large number of vacuum tubes, each having a limited life, might be somewhat troublesome.

The third time standard in fairly common use has a very special form of tuning fork preferably maintained in vibration by vacuum tubes. Standards of this kind are said to operate with a precision of one part in a million, which would correspond with an error less than one-tenth of a second per day.

The effect of variations in temperature on these time standards may be detrimental and therefore it is customary to maintain them at a very constant temperature. Consequently compensating means are usually provided for the purpose of minimizing temperature effect.

Several years ago the writer, who has been concerned with problems of speed and frequency regulation that are of course based on time measurements, determined to build if possible a more simple form of secondary time standard which would be free from some of the objectionable features of the very accurate devices commonly used. Utilizing the vibrations of a stretched string or wire seemed to offer attractive possibilities. Every one knows that a piano or violin string gives out a fairly constant musical note when set in vibration. It is evident, however, that the note depends on the tension of the wire and that it would be very difficult indeed to provide absolutely constant tension through the usual form of mounting. The very fact that frequent tuning is necessary makes this clear.

The force of gravity as a means of providing tension appeared desirable. Experiments at first took the form of a vertical wire stretched over two bridges and tensioned by a weight. If the distance between the two bridges could be held exact it appeared as though such a wire should have a very constant rate of vibration. The accuracy of this arrangement was only fairly satisfactory for several reasons. These were irregular pressure on the wire over the bridges, absorption of a portion of the vibrating energy by the structure which held the bridges, a tendency of the wire to vibrate in different modes, etc.

Gradually the device evolved into the form of a vertical wire or strip supported rigidly at its upper end and tensioned by a weight at its lower end. This was set into vibration by a force supplied at its central point so that when vibrating it consisted of a single loop with nodes at both ends. Many methods of imparting vibrations were tried but eventually a very simple vacuum-tube coupling was adopted which supplied energy through the medium of a permanent bar magnet

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The author gratefully acknowledges close co-operation during a long period of research by his associates of the Warren Telechron Company, especially Charles A. Ellis.

that also constituted loading at the middle point of the stretched wire.

In order to compel vibration in a definite plane the vibrating element at first consisted of a narrow strip of metal which was stiff edgewise, but later it was found that a round wire would vibrate in a plane provided the driving magnet was accurately centered.

There are numerous difficulties in a device of this kind. In the first place, more than one mode of vibration may be established, for the wire can obviously vibrate in sections and it can also vibrate axially. Very soon it was discovered that if there were a fairly close correspondence between the normal rate of axial vibration of the system as a whole, including the weight, and one or more harmonics of the transverse vibration, the performance was wholly unsatisfactory. This meant that it was necessary to avoid certain proportions which involved frequency, length, and loading of the wire. Then it was found that a plain stretched wire or strip mounted in the manner described gave a frequency which increased rather rapidly with the amplitude of vibration so that in order to maintain a definite rate it would be necessary to maintain a very constant amplitude.

The effect of temperature on the vibrating wire arranged in this manner is rather complicated. Variations in length due to this cause need not be troublesome because the wire can be made of a material like Invar which has a nearly constant length over a wide range in temperature, but the effect of temperature on the modulus of elasticity of the vibrating materials is an important factor. A vertical wire tensioned by a weight has elastic stiffness in a transverse direction, that is to say, it behaves somewhat like a beam fixed at both ends vibrating under a load at its middle point. The transverse elastic stiffness has the effect of increasing the frequency of vibration beyond that caused by the tensioning weight. The elastic stiffness at a given temperature varies very rapidly in inverse proportion to the fourth power of the diameter of the wire and in direct proportion to the cube of its length.

Common materials which might be used for this purpose like steel, brass, tungsten, beryllium alloys, etc., become less stiff, that is to say, their modulus of elasticity decreases with increasing temperature. Consequently, vibrating wires made from these materials will have decreasing frequency as the temperature rises. Fortunately there are certain materials, especially nickel-steel alloys having composition very similar to Invar, that grow more stiff with increasing temperature. Vibrating wires made from this kind of material will show an increase in frequency as the temperature rises. The temperature coefficient of the elastic modulus of Invar is especially high, being in the neighborhood of 500 parts per million per degree centigrade. The temperature coefficient of the modulus of elasticity in the opposite direction of some of the other materials mentioned is much less, although still many times greater than the temperature coefficient of the length expansion.

It is possible to control the magnitude of the effect which temperature will have on the frequency for a given kind of material by planning the proportions of length, diameter, and loading of the vibrating wire. The smaller the diameter and the greater the length the less will be the effect of temperature changes which influence the elasticity of the material. For convenient lengths, however, and with reasonable loading within the elastic limit of the material used, there will usually remain frequency variations when there are temperature changes. However, these variations may be made as small as desired if advantage is taken of the opposite sign of the temperature coefficient of the elastic modulus by making the vibrating wire in part of a substance like Invar, having a temperature coefficient which gives greater stiffness with rising temperature and in part of another material like beryllium copper which becomes

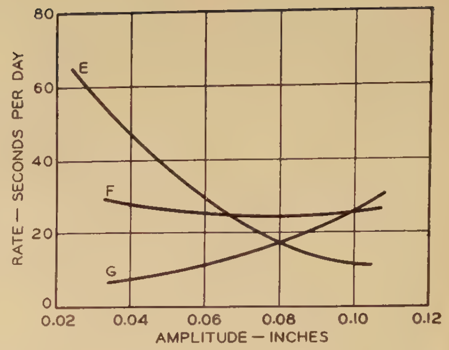


Figure 2. Rate compensation for changes in amplitude by means of r resilient bow

E—Overcompensated—bow length 2.82 inches

F—Full compensated effect—bow length 2.50 inches

G—Undercompensated—bow length 2.27 inches

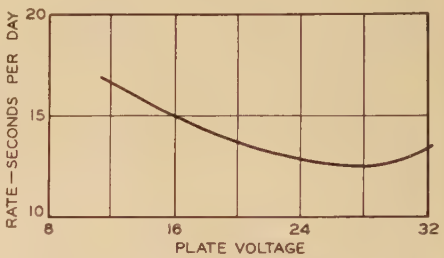
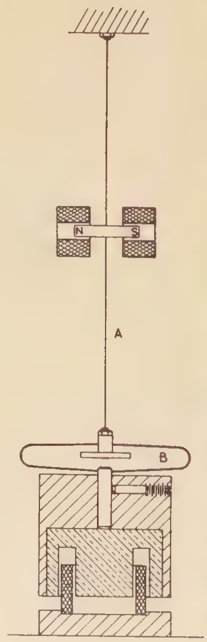


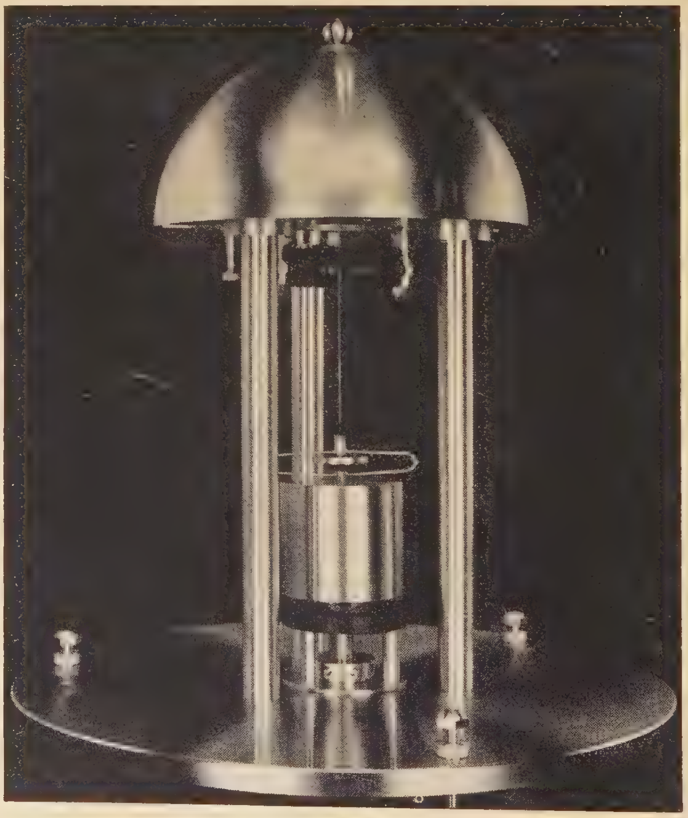
Figure 3. Effect of plate voltage upon time rate

Figure 4. Complete vibrator unit

Diameter of base 14 inches

Figure 1 (below). Diagrammatic representation of vibrator assembly in section





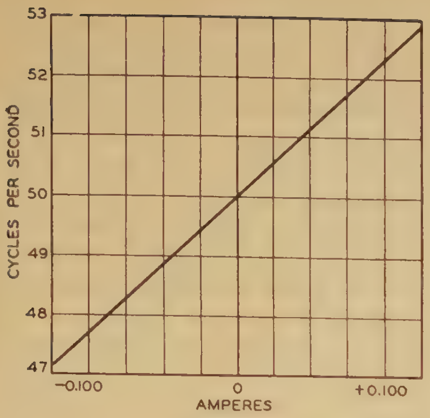


Figure 5. Relation between current in regulating coil and frequency

less stiff with rising temperature. If the relative lengths of these two materials are properly chosen the temperature effect of one may be made to cancel the temperature effect of the other as regards stiffness and if there is a slight residual of length expansion that may also be neutralized by a preponderance of one kind of elastic alteration.

There are alloys like elinvar which have a nearly constant modulus of elasticity with regard to temperature but in the experiments which have been made with this kind of material the reduction of temperature effects has been less satisfactory than by the very simple method of combining materials which have opposite signs of elastic temperature coefficients.

Further means of eliminating any slight residual temperature effect may act by opposing or adding to the gravity force of the weight by an adjustable element such as a weak spring or a thermosensitive magnet which will aid or oppose the tensioning force as the temperature changes.

Variations in rate caused by changes in amplitude can be corrected in a very simple manner. The normal increase in rate with increase in amplitude results because the vibrating wire is comparatively rigid axially so that it forms a connection having a nearly fixed length between the weight and the upper support. The weight has very considerable inertia and it tends to remain at rest in a position where the average force which it exerts on the vibrating wire is constant but the instantaneous force varies. The relationship is obviously slightly different for each amount of amplitude.

The instantaneous effect of the force exerted by the weight results in a component at the center of the vibrating wire tending to restore it to its mid-position and this component of gravity force is proportional to the tangent of the angle of deflection of the vibrating wire. If the component of force which is designated as restoring force were exactly proportional to the displacement of the wire, there would be harmonic motion and isochronism. Then there might be no change in rate with change in amplitude.

However, because of the inertia of the weight and slight axial elasticity of the wire, the instantaneous component of force varies in a different manner, being larger than the tangent of the angle for large angles of deviation and less than the tangent for very small angles. For this reason the frequency rate increases with the amplitude of vibration. In the case of an ordinary clock pendulum the reverse is true. There the rate decreases with increase of amplitude.

It has been found that if an elastic connection be interposed between the weight and the lower end of the vibrating wire, the component of gravity force which tends to restore the wire to its mid-position more nearly approximates proportionality to the tangent of the deflection angle, and if this elastic coupling between the weight and the wire is sufficiently soft the wire will actually vibrate with a slower rate as the amplitude increases.

These facts have resulted in the design of a vibrating element which consists in part of a member that is comparatively stiff in an axial direction corresponding to the wire *A* in figure 1, and another member an elliptic spring *B* which is decidedly elastic in the same direction. The wire, however, is free to vibrate transversely while the spring is comparatively rigid in that direction.

A good result can be obtained by the use of other types of springs. For example, the vibrating wire may consist of an upper portion flexible transversely and stiff axially with the lower portion in the form of a spiral spring which is flexible in both directions. The main desideratum is that the elastic flexibility of the spring member in a vertical direction shall have that scale of stiffness which insures that the frequency rate of transverse vibration of the vertical element will be approximately the same over a reasonable range in amplitude.

While it might be possible to compute the exact dimensions of the elements that are involved in the combination, the problem would be a very complicated one, but it is fairly easy to find the correct proportions by experiment. Figure 2 shows several curves which illustrate the relation between amplitude and rate of a certain vibrating wire when coupled to the tensioning weight by elliptic springs of different lengths. These curves indicate very clearly that with the correct stiffness of elliptical spring the rate of the vibrating wire scarcely changes over a fairly wide range in amplitude.

Various methods of driving the vibrating wire have been tried, all of which involve some form of coupling between the wire and a vacuum-tube circuit. One very satisfactory form consists as shown in figure 1 of a small permanent bar magnet of cobalt steel very rigidly attached at the center of the wire. One end of this magnet projects into a pickup coil and the other end is surrounded by a driving coil. These two coils are connected respectively to one grid and plate of a twin-triode tube.

The other half of the tube is used for amplifying the voltage of the first stage. In order to avoid picking up external frequency in the first stage a $22^1/_2$-volt plate battery is used. The heater current and the other plate supply voltage come from a regular power circuit. A second tube further amplifies the energy so as to deliver about two watts at 120 volts which is adequate to operate a Telechron clock motor. For greater power a small amount of this output is diverted to another stage of amplification.

The relation between the plate-battery voltage and the time rate in seconds per day is shown in figure 3. The amount of current drawn from the plate battery is less than a tenth of a milliampere so that reduction of battery voltage takes place very slowly indeed. The amount of energy required to keep the string in vibration at ordinary atmospheric pressure is less than half a milliwatt.

The effect on the rate of barometric changes in the atmosphere is extremely small; apparently less than a tenth of a second per day for the ordinary range. Therefore it does not seem necessary for most purposes to provide an air-tight enclosure for this time standard but the instrument is so constructed that a bell jar can be placed over it. The compensation for variations in temperature is so accurate that for most purposes temperature control is unnecessary.

The instrument can be constructed so that 100 degrees Fahrenheit difference in temperature will produce less than one second per day variation in rate. Where the surrounding temperature is not likely to vary more than 10 degrees Fahrenheit the error due to this cause is negligible for many purposes. Probably the best location for an instrument of this kind is on a foundation of its own in an underground enclosure where the temperature would be comparatively constant.

For the purpose of measuring the prog-

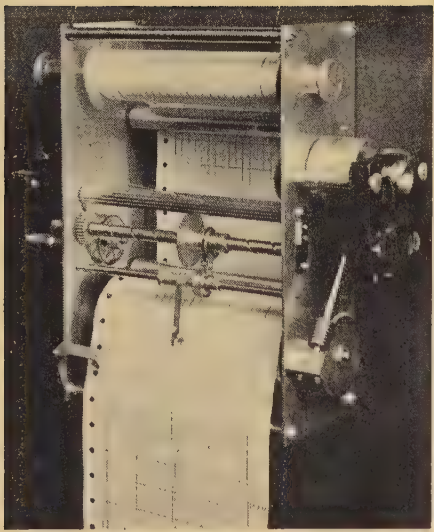


Figure 6. Graphic time comparator

ress which has been made in reducing temperature effects one of these compensated time standards has been exposed to comparatively wide temperature variations for a period of ten days. This was done by subjecting it to rather high room temperature during working hours and then cooling the room at night by shutting off the steam heat and opening the windows to the outside New England air.

The 24-hour average temperature varied from 65 to 81 degrees Fahrenheit and intermediate changes as great as 40 degrees Fahrenheit were observed. Over this period the average rate was one-tenth second per day fast. The greatest error was four-tenths second per day. No attempt has yet been made to determine the extreme precision which can be obtained with this new instrument but the indications are that time can be measured with an error less than one-tenth second per day when favorable conditions are provided.

There is an additional feature of this new time standard which may be of great importance for certain purposes. The weight which tensions the vibrating wire and very definitely controls its frequency is of course constant under the influence of gravity. Forming a part of this weight is a cylindrical Alnico magnet and in the air gap of this magnet there is a coil of fine insulated wire.

When a measured direct current is passed through the coil the reaction between the magnetic flux and this current will produce a force in the same direction as the gravity force but plus or minus in sign depending upon the direction of the current. The value of this current may be accurately adjusted by a graduated potentiometer or resistance so that the frequency rate of the vibrating wire may be controlled with great precision over a moderate range from a distant point. Figure 5 shows the relation between frequency and control current.

The amount of energy necessary to adjust the rate of a 60-cycle time standard over a range of plus or minus one cycle by this magnetic method is less than one-tenth of a watt. Consequently, there are no important heating effects which might be disturbing and the control apparatus may be very simple.

In order to study the performance of these new time standards, an interesting form of graphic comparator illustrated in figure 6 has been constructed. This consists essentially of a long revolving screw arranged transversely with respect to a moving strip chart. The screw is driven through gearing from a Telechron synchronous motor. On the screw there is a nut carrying a gear which is made to rotate by another Telechron motor. The gear reduction from this second motor to the nut is such that the screw and the nut normally revolve at the same speed and in the same direction. Any axial motion of the nut is transmitted to a light slider which carries a pen making contact with the paper chart.

Thus the line drawn by the pen indicates the axial position of the nut at any instant. One of the two synchronous motors is connected to a standard source of frequency and the other to a source of frequency being studied. This can for example be a power system in which case the line drawn on the paper chart will be an accurate record of the integrated system frequency. A small section of such a chart is shown in figure 7, curve *Q*. This record was made on one of the big eastern power systems and shows on a very open scale the integrated speed fluctuations which are continually taking place. In this particular chart the fine graduations are one-fifth of a second or 12 cycles apart. Consequently, it is possible to read extremely small frequency errors with high precision, far exceeding any of the ordinary graphic frequency recorders.

The slope of the curve is a measure of the instantaneous frequency. The transverse lines in this particular record are one hour apart. Consequently, a frequency error of $^1/_{100}$ of a cycle corresponds with a time error of six-tenths of a second per hour or an angle of about 45 degrees. An error in frequency considerably less than $^1/_{1,000}$ of a cycle can easily be seen. The kind of speed regulation on a system whether by ordinary governors supplemented by manual adjustment or by some type of automatic frequency controller, will determine the form of curve *Q* so that considerable information may be obtained from this record.

Figure 7, curve *S*, which is made by comparing one of these new time standards running at fixed temperature with another operating at variable temperature, shows very clearly the high precision of the instruments. The temperature variations to which the second instrument was subjected are shown in curve *T*. It is interesting to compare curve *Q* with curve *S* and observe how far short of perfection system frequency is at the present time, although for most commercial purposes it is very satisfactory.

For certain requirements, precisely controlled frequency of this kind may be very important. For example, in driving large telescopes in astronomical observatories it is necessary that the image of a star

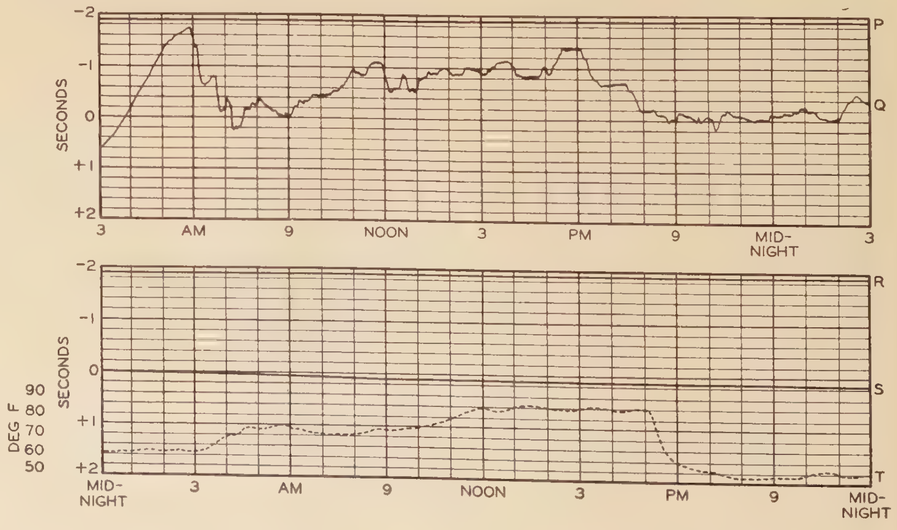


Figure 7

P and *R*—Reference lines drawn by stationary pen

Q—Integrated frequency of power system

S—Time rate with corresponding temperature variation *T* of vibrator unit

or other heavenly body should be held stationary in the field of the telescope for the purpose of making photographs which sometimes require hours of exposure. Since the telescope is swinging about an axis parallel to that of the earth one might suppose that the rate of angular motion should be exactly uniform to follow a star. Actually, it is necessary to vary this motion slightly because the refraction by the earth's atmosphere increases steadily from the zenith to the horizon.

Obviously, one of the best means of driving a telescope is a synchronous motor but if such a motor is supplied with alternating current of perfectly constant frequency some mechanical means is needed to adjust for the slight apparent error in stellar motion. The difference in motion of other heavenly bodies such as a planet or the moon would of course require a much greater adjustment of the rate.

From this explanation it will be appreciated that this new time standard contains within itself means for extremely precise and easily controlled rate adjustment and that it can supply alternating current to a synchronous motor driving a telescope so that the latter will accurately follow the motion of a heavenly body. The method of adjustment in the case of a star where the rate varies from the zenith to the horizon may become automatic through the use of suitable cams. Thus after the telescope has once been focused on a star the image will remain stationary in the telescopic field without any manipulation by the observer.

Utilization of this instrument for the purpose of driving telescopes is only one of a great many possible applications. To the scientist and engineer it may prove another useful implement in the endless campaign of progress.

Discussion

C. W. La Pierre (General Electric Company, Schenectady, N. Y.): The ordinary time standard, as we know it, is usually based upon either the gravitational constant or upon the physical constants of a particular material. The pendulum is an example of the first, and tuning forks and crystals are examples of the second. Mr. Warren has combined these two means of getting a time standard in such a way as to provide gravitational rate control such as is used by the pendulum with vibrational frequencies ordinarily associated with tuning forks. In this way, he has made provision for a very desirable feature, namely, ability to adjust the frequency of vibration over a fairly wide range. To those who have long desired an adjustable-frequency time standard, the new method opens many possibilities. Unfortunately, it also introduces into the time standard many of the difficulties of each of the previous basic methods.

As compared with the tuning fork, for instance, we find that the rate change for changes in amplitude is inherently somewhat worse than the corresponding change for a tuning fork. Mr. Warren has pointed out ingenious means for compensating for this amplitude effect.

With recent vacuum-tube circuits, the effect of amplitude change on frequency might be minimized by stabilizing the amplitude with the tube circuit. How this can be accomplished in tuning forks is described in Patent No. 2,147,492, M. S. Mead.

The ability of Mr. Warren's device to operate over a considerable frequency range by simple adjustment of current in a regulating coil is unique among standard-frequency sources. Unfortunately, we cannot regulate current to the same precision as we desire frequency. Otherwise, we could use current as the basic control for our frequency standard. In Mr. Warren's system, the error in current setting will result in a corrresponding error in only that part of the frequency which is dependent upon the flow of current. For instance, from Mr. Warren's figure 5, one-tenth ampere of current produces a change in frequency of approximately 2.3 cycles or a change in time of approximately 4,000 seconds per day. Therefore, if it is desired to operate 2.3 cycles from 50 cycles with a precision of one second per day, it would be necessary to maintain the current constant to one part in 4,000. This might involve some problems over a considerable period of time. On the other hand, such a departure from the normal frequency is not to be obtained by any of the more usual mechanical timing oscillators.

In addition to rate changes due to amplitude and possibility of frequency adjustment, Mr. Warren finds with his device, as well as with the other devices, that temperature compensation is extremely important. Quartz crystal oscillators having a temperature coefficient of one part per million per degree centigrade are common. However, the coefficient for quartz varies with ambient temperature, and it is difficult to secure this coefficient except over a limited range of, say, -30 to $+50$ degrees centigrade. Tuning forks can be readily made with coefficients less than ten parts per million per degree, and by special heat treatment this might be reduced to about two parts per million. Satisfactory temperature regulation on fork and crystal oscillators is relatively easy to secure, although there is always the possibility, if not probability, that the thermostatic regulator will fail and cause difficulty. Mr. Warren's figure of approximately two parts per ten million per degree centigrade indicates that he has achieved an excellent temperature compensation in this device as compared to what we ordinarily produce in crystal or tuning-fork oscillators.

Arnold White (nonmember; General Electric Company, West Lynn, Mass.): The author should be complimented for bringing this new instrument to the attention of the industry. A real need exists for a simple secondary standard of time, free from the objectionable characteristics (as noted by the author) of the standards now in use. Such a standard would enable the meter and instrument engineers to develop new test equipment which would expedite and simplify the calibration of watt-hour meters and frequency meters. For example, in the calibration of watt-hour meters, the number of revolutions of the meter disk must be counted and timed. This usually is accomplished by the test man holding a known load while visually counting and timing (by means of a stop watch or clock) the revolutions of the meter disk. This presents many chances for personal errors. Any methods frequently used to calibrate watt-hour meters, employing a light beam, photoelectric cell, and synchronous timer to count and time automatically the revolutions of the meter disk, offers a large saving in time and reduces the chances for personal errors to a minimum. The successful operation of this system depends on the availability of a source of constant frequency (such as is obtainable from a quartz oscillator or tuning fork) for operating the synchronous timer. However, due to the large investment in the source of constant frequency, this system, up to the present, has only been within the reach of the larger laboratories. It is hoped the new standard of time will bring this method of meter calibration within the reach of the smaller laboratories. The author does not show what effect, if any, local interfering vibration has upon the constancy of frequency. It is believed the same type of interference received through the base of a tuning fork and affecting its frequency may also affect the frequency of the vibrator unit thus necessitating the use of an interference absorbing mounting. The author suggests mounting the vibrator on a pier. We have had some experience with mounting a tuning fork on a pier. It was found that a pier did not materially reduce the interference from the earth tremors caused by trucks and other heavy machinery operating in the vicinity of our building. After trying several forms of Julius suspensions with little success, we found that a piece of slate (taken from an old switchboard) about two feet square and two inches thick mounted on four soft rubber balls about four inches in diameter (purchased at a local five-and-ten-cent store) relieved the situation entirely.

Henry E. Warren: Referring to C. W. La Pierre's comments, in addition to the very great reduction in rate change for changes in amplitude by the method suggested in the paper, the vacuum-tube circuit is so arranged as to hold the oscillating wire at almost constant amplitude so that time errors due to variations in voltage are very small indeed. The adjustment of rate by variations of the current in the regulating coil which adds to or subtracts from the gravity force would not ordinarily be used over a large range or for a long time. This feature is most important perhaps in regulating the angular motion of large telescopes where the rate variations due to changes in the atmospheric refraction between the zenith and the horizon and errors in the gear-tooth spacing, etc., are very small so that there should be no difficulty in holding the regulating current to the precision desired. If such a

Testing of Distribution Arresters

HERMAN HALPERIN
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THE testing of distribution lightning arresters, especially those removed from service, has increased sharply in recent years. Such testing by utilities is considered in this paper as distinct from design and routine tests made by the arrester manufacturers.

While check tests on new designs of line-type distribution arresters (rated at 15 kv and less) are sometimes made by utilities to insure that new arresters have the desired characteristics and meet specification requirements, yet few utilities make routine tests on new arresters. There seems to be little need for such routine tests in view of the good quality of present-day arrester design, manufacture, and factory tests.

Arresters in service, however, are mostly of types made about five years ago and earlier and in many cases are now known to have had originally or to have developed some deficiencies. Arrester failures or lack of adequate lightning protective characteristics have not usually been sufficient to warrant wholesale replacements or the trouble and expense of testing at the installations. In a very few cases operating experiences have justified complete replacement of some types of arresters manufactured 15 to 20 years ago.

Arresters removed from service incidental to other work, however, may or may not be in suitable condition for reinstallation. Routine inspection of such arresters, of course, serves only to eliminate those which are broken or damaged externally. In a few cases, operating experience has demonstrated that certain types should be junked upon removal.

For a large majority of arresters removed from service, information in this paper indicates that routine testing of the proper type makes available at relatively small expense arresters which are suitable for re-use. Blind junking of all distribution arresters removed from service, regardless of type, seems to be wasteful.

At the request of the AIEE lightning arrester subcommittee, the experiences of utilities with various test methods were obtained by the author for technical study.

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The author acknowledges the co-operation of 29 utilities in furnishing extensive data and the valuable assistance of E. H. Grosser in preparing the paper.

Present Status of Arrester Testing

A questionnaire was sent in January 1939 to 55 operating companies. Replies were received from 52 companies.

Twenty-nine companies reported that tests of various types are an established procedure for distribution arresters, with only six of the companies testing new arresters. These companies included most of the largest utilities and a number of the smaller ones, all located east of the Rocky Mountains.

Table I shows a summary of test methods in use for new arresters and for arresters removed from service, as well as related cost data where furnished. Numbers were arbitrarily assigned to the 29 companies reporting tests. These utilities have been making tests on used arresters for periods ranging from 1 to 11 years, except that one company has been making 60-cycle withstand tests on removed arresters for 24 years. Six companies also test new arresters and one tests arresters at installed locations. Usually more than one type of test is applied by each utility.

Over 150,000 arresters removed from service due to causes other than trouble associated with the arresters themselves have been tested by the 29 companies. Probably over 40,000 arresters when new have been given routine tests, mainly by two utilities.

A detailed analysis of the data submitted in reply to the questionnaire is given in the following discussion, taking each type of test separately. As all of the 29 reporting companies made tests on removed arresters (see reference 1 for a description of some test methods) such tests will be discussed first.

Tests on Arresters Removed From Service

IMPULSE TESTS

Routine impulse tests on removed arresters are made by three of the companies reporting. Company 7 makes impulse tests on 3-kv arresters in accordance with AIEE Standards No. 28 for lightning arresters, using a portion of a 650-kv surge generator with 2,300-volt power follow supply. Characteristics are observed on a cathode-ray oscilloscope. Company 8 follows AIEE Standards No. 28, except that it uses surge currents of about 3,000 amperes with a 0.5x150-microsecond wave. This company uses a 100-kv surge generator with power follow supply at 2.8 and 5.6 kv for 3- and 6-kv arresters, respectively. Surge voltage is measured by sphere gap. Company 20 uses a 100-kv surge generator with a 1.5 x 40-microsecond wave and 1,200-ampere surge current. A 60-cycle voltage of 4 kv is applied to 3-kv arresters during impulse tests. This is quite severe.

Arresters rated at 3 kv are rejected by company 7 if their spark-over voltages are outside the range 8 to 14 kv or 14 to 20 kv, depending upon arrester manufacture. These limits, which agree reasonably well with the published range[2] of 12 to 22 kv for new arresters, were established by values found for new arresters.

Company 8 rejects arresters which have discharge voltage (*IR* drop) at 3,000 amperes exceeding 30 to 37.5 kv for 3-kv arresters and 35 to 47 kv for 6-kv arresters, the values used depending upon manufacture. These limits, which exceed the published maxima[2] of 15.5 and 30 kv by large margins, were selected to eliminate arresters having characteristics too far above the average for new arresters, and may be too liberal.

Company 20 has no limits other than failure to interrupt power follow current on surge test.

No information on rejections was given by company 7. For company 8, 4,167

gross shift in frequency as two cycles were to be held over a period of a day a major correction could be readily made by adding or subtracting suitable weights.

External vibration if transmitted to the oscillating wire of this time standard may have a detrimental effect but this effect is greatly reduced in the instrument itself by the use of soft springs which support the heavy mass to which the upper end of the wire is fastened. Further absorption of external vibration by simple means like that suggested by Arnold White seems desirable for locations where vibration is considerable.

arresters, or about five per cent of all arresters returned from service, have been rejected for failure to meet impulse and 60-cycle withstand tests. Their records do not differentiate between the two causes of rejection. Only about one per cent of the used arresters tested by company 20 have been rejected on impulse tests.

The impulse test is the only test which serves to indicate the ability of the arrester to protect equipment and to interrupt power follow current. A relatively simple test method appears to be that of company 20, if follow current at a suitable voltage is supplied by a transformer having bushings gapped to an impulse flashover voltage slightly higher than the normal characteristic of a satisfactory arrester. Inadequacy of the arrester is indicated either by bushing-gap flashover or by automatic opening of the supply to the transformer.

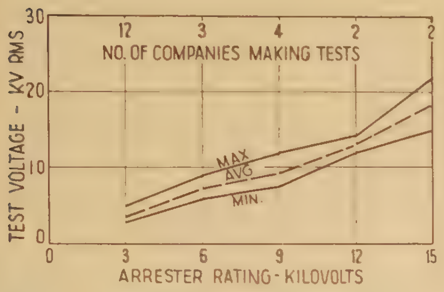

Figure 1. Sixty-cycle withstand test voltages in use for distribution arresters removed from service

Thorough testing for impulse characteristics should follow AIEE Standards No. 28.

The experience of companies 8 and 20 indicates that changes in the impulse characteristics of arresters occur in service in relatively few cases, and that impulse tests are not needed ordinarily. Company 17 also found this indication based on impulse tests on a few moderately corroded arresters of one type.

Sixty-Cycle Withstand Test

As the name implies, this test consists in applying a predetermined value of low-frequency voltage across the arrester terminals for a definite time, usually one minute. Spark-over of the arrester gap, evidenced by appreciable current flow in the circuit, and opening of the power supply by overload relay, is taken as cause for rejection.

Test voltages in use by 13 companies are summarized in figure 1. Tests are made at voltages ranging from 83 per cent to 167 per cent of arrester-voltage ratings, the average being 113 per cent. Five companies test at rated voltage.

Five companies reported data on rejections based on the 60-cycle withstand test. For tests at average voltages of 1.0, 1.1, 1.3, 1.3, and 1.5 times rated arrester voltages, the rejections in this test were roughly 0, 5, 0.1, 15, and 1.5 per cent, respectively. These results, which are probably obscured by other factors, give no indication that the higher test voltages result in a larger number of rejections.

Seven of the companies have dissected arresters rejected in the 60-cycle withstand test. The most common findings were as follows: corroded gap assemblies (seven companies); moisture in gap assemblies, gap welded, foreign particles from the valve element in gap assemblies, porcelain gap spacers cracked, and valve element punctured or damaged (each reported by one company). One utility which found corrosion in many cases reported that no trouble was apparent in some dissections of rejected arresters.

It is probable that test voltages equal to, or little more than, the rated arrester voltage could be depended upon to reject only those arresters having serious internal defects. The test, in general, is apparently not severe, since much higher percentages were rejected in other tests by other companies. Arresters rejected in this test have generally, but not always, revealed internal defects when dissected. Nine of the 13 companies making 60-cycle withstand tests, however, state that the test is satisfactory; no statement was received from four companies.

This test, even when used at slightly above rated voltage, is to be recommended only because of its simplicity. It should not be considered an infallible test for defects, but should be used in conjunction with other tests.

Sixty-Cycle Breakdown Voltage Test

This test has been used by 15 utilities, for periods ranging from 1 to 11 years, to check arresters returned from service. As shown in table I, 9 of the 15 companies also make 60-cycle leakage-current tests, using the same circuit as for the breakdown test, and three companies make breakdown tests and Megger or resistance measurements.

The circuits used for making 60-cycle breakdown tests consist of a variable-voltage testing transformer or a transformer with induction regulator or tapped autotransformer in the low-voltage circuit, a voltmeter connected to the transformer voltmeter coil or to a separate potential transformer, or (company 22) an electrostatic voltmeter, and a series resistor for limiting the current in the circuit at arrester breakdown. This resistor may be located in either the low-voltage or high-voltage circuit, as has been illustrated.[1]

Eleven of the companies employ resistors in the high-voltage circuit, two (one of which, having two test circuits, is also included in the preceding group) use resistors in the low-voltage circuit, two use no resistors but depend on the impedance of the testing transformer, and one gives no information. The ohmic values of series resistors used range from a fraction of a megohm to 100 megohms. These resistances were selected to limit the current through the arrester during breakdown to values, calculated from data submitted to the author, ranging from less than 1 milliampere to 25 milliamperes. The average of maximum permissible currents in tests by nine companies was approximately 14 milliamperes. One of these companies used two values of limiting current, 10 and 20 milliamperes, for different makes of arresters. Another company, not included in this average, used an overcurrent relay to trip the low-side breaker in about 15 cycles for currents of 15 to 35

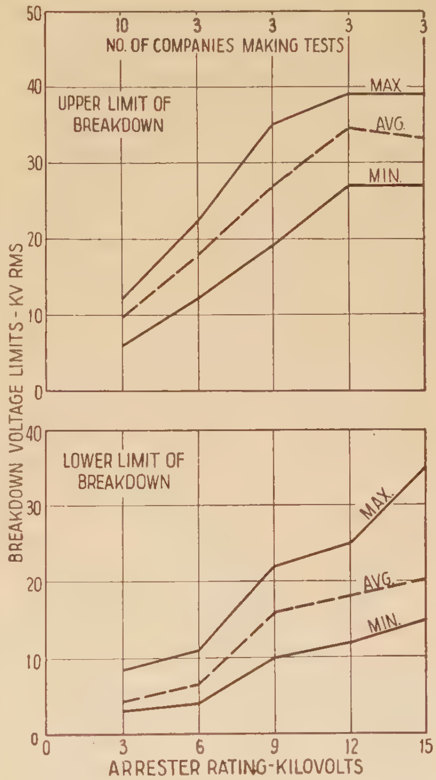

Figure 2. Acceptable limits of 60-cycle breakdown voltages in use for arresters removed from service

milliamperes, but used no series resistor.

Only two companies regularly make correction for the voltage drop in the high-side series resistor, in determining the arrester breakdown voltage. A third company makes this correction only for arresters having resistance shunted gaps, where the leakage current prior to breakdown is appreciable. For arresters with ordinary gaps and such that they would not be rejected in the leakage-current test, the drop through the current-limiting resistor would probably be negligible. Where the current-limiting resistor is placed in the low-voltage circuit, no correction, of course, applies, since voltage measurement is always made with respect to the high-voltage circuit.

Limits of acceptable 60-cycle breakdown voltage are shown in figure 2. Minimum acceptable breakdown voltages for arresters returned from service range from 0.7 to 2.8 times arrester rated voltage, and maximum acceptable breakdown ranges from 1.8 to 4.0 times rated voltage. The low value of 0.7 applied to a case where the operating voltage of the arrester was a minor fraction of its rating. For 14 companies the average acceptable limits were about 1.3 times the rated voltage of the arrester for the minimum breakdown and 3.0 times the rated voltage for the maximum breakdown. This is in fair agreement with the values of 1.5 to 3.0 times rated voltage which were previously suggested.[1] The 15th company has established no specific limits, but stated that a number of arresters have been returned to service with breakdowns as high as 3.4 times rated arrester voltage.

Rejections for low breakdown voltage, as reported by six companies, ranged from 0 to 6.7 per cent (average 2.0 per cent) of arresters tested. High breakdown values were reported by five companies to have resulted in rejections of from 0 to 2.8 per cent (average 1.4 per cent) of arresters given the breakdown voltage test. One company reports rejections of one per cent for unsatisfactory breakdown action, that is, gradual breakdown, or high resistance after breakdown. Total rejections by seven companies in the 60-cycle breakdown voltage test averaged 4.1 per cent, and ranged from 0 to 8.8 per cent.

An attempt was made to determine whether the rejections in this test were related to the rejection limits used. No correlation could be found, either for lower or for upper limits.

Arresters rejected in this test have been dissected by nine companies, to determine

Table I. Tests Made on Distribution Arresters by Utilities

Company Number	Test Method: Impulse Voltage	60-Cycle Tests: Withstand Voltage	Breakdown Voltage	Leakage Current: Micro-ammeter	Milli-ammeter	Neon Tube	Megger or Resistance Bridge	Radio Interference or Ionization
Number of years test has been in use on arresters removed from service:								
1		1						1
2		24						
3		0					4	
4		7						
5		0	Several					Several
6		9						9
7	7	3					3	
8	5*	9*						3*
9			1	1			1	1
10					10**			
11			1	1				
12			4					
13			10		3			3
14			1½					
15			1½				1½	
16			2*	2*				2*
17			6	6				
18			10*					10
19		5						
20	2	2	2				2	2
21		9*	7*		9*			
22			11		11	11		
23			2	2				
24		6						6
25			2*			2*		
26		9*						9
27		1						
28		6						6
29							5	
Average years in use	4.7	7.0	4.4	2.4	8.3	6.5	2.8	4.7
Number of companies using test for:								
New arresters	1	3	4	1	1	1	0	2
Used arresters	3	13	15	5	4	2	6	12

* These tests are also made on new arresters.
** Approximate or estimated.

the causes for unsuitable breakdown values. Usual findings were: gap electrodes pitted, burned, or springs broken (six companies); gap assembly corroded or contained moisture (five companies); foreign particles in gap assembly (one company); valve element damaged or wet (two companies). The most usual causes for low breakdown were gaps pitted and gaps shorted by corrosion or burning; for high breakdown, damaged gaps or deteriorated springs, resulting in increased gap separation. The one company (number 17) giving unsatisfactory breakdown action as cause for rejection finds each of the above causes to be responsible in varying degree. One company (number 14) included above, however, stated that no correlation was found for high breakdown voltage, and another (number 15) that, in general, no correlation seemed to exist between test results and arrester condition.

Two utilities sent in the results of dissections in some detail. One (number 12) found low breakdown voltage to be associated with pitting or corrosion of gap assemblies in each of 11 arresters dissected, but dissections of 14 arresters having breakdowns of from 4.1 to 5.6 times rated voltage failed to reveal any defects in nine cases. The other (number 25) found deteriorated metal parts in several arresters rejected for low breakdown.

A review of this test method, which is extensively used, indicates that it is mainly useful as a means of detecting internal defects, particularly in metal parts, when applied in conjunction with leakage-current measurements or megger testing. While low breakdown voltage is generally associated with defective conditions, this has not always been found for high breakdown voltages. It seems undesirable to employ the same upper breakdown limits for all makes and types of arresters used on a system, but such limits should be determined for each type by tests on good arresters. The test is more informative than the 60-cycle withstand voltage test.

Sixty-Cycle Leakage-Current Measurements

Such measurements have been used for periods ranging from 1 to 11 years by ten companies. Only one utility (number

Table I (Continued). Tests Made on Distribution Arresters by Utilities

Company Number	Number of Arresters Tested: Arresters Removed From Service	Number of Arresters Tested: Part or All of New Arresters	Per Cent of Arresters Rejected by Test: Arresters Removed From Service	Per Cent of Arresters Rejected by Test: New Arresters	Testing Cost per Arrester Tested	Testing and Rehabilitating Cost per Arrester Returned to Stock
1	500	0	5.0		—	$0.50 to 0.75
2	8,500	0	1 to 2		—	0.84
3	1,200	0	58			
4	?	0	?			
5	500/yr.	0	?		—	0.50 to 1.00
6	?	0	6 to 10		$0.10	1.10**
7	350	0	?		0.50 to 0.75	—
8	85,000	10,050	5.6	0	0.04	0.30
9	717	0	17		—	0.60**
10	16,000 (in 4 yrs.)	0	16			
11	500	0	24		—	0.15 to 0.25
12	2,375	0	2.9		0.15 to 0.25	1.30 to 1.40
13	286♯	0	20		0.25	2.00**
14	200	0	40†			
15	1,485	0	9.8		—	0.28**
16	1,477	195	23	16	0.50	0.94
17	6,600	2,200‡	8.3	Few	0.35	1.12
18	?	?	Few	Few		
19	393	0	15		0.20**	—
20	1,919	0	3.0		0.35	—
21	6,882	25,508	7.2 (incl. new arr.)		—	0.75 to 1.00
22	4,571	0	20†		—	0.60
23	4,100	0	10			
24	?	0	?		0.10**	
25	?	?	?	?		
26	?	?	30**	0		
27	20	0	0			
28	192 (1938)	0	22			
29	?	0	<5			
Total or average	143,267+	37,953.+	9.4** (weighted average)		$0.27 (average)	$0.83 (average)

† Includes rejections due to mechanical defects.
? Means no data submitted, or utilities had no records readily available.
♯ Since 1936.
‡ Routine test on new arresters has been discontinued by this company.

10) tests for leakage current with no corresponding breakdown voltage test.

In general, the same test circuit is used for leakage and breakdown measurements, and consists of a variable high-voltage supply to the arrester, and series meter for measuring the leakage current (and small charging current) of the arrester under test. No attempt is made in most cases to shield the meters from stray fields as this is done by only two companies reporting. One company (number 10) wets down arresters before testing.

Current through the arrester at rated voltage is measured by five companies by means of microammeters, capable of indicating minimum values ranging from 4 to 50 microamperes. Three companies (numbers 10, 21, and 22) use milliammeters with minimum readable currents from 100 to a few hundred microamperes. Company 22 uses the milliammeter partly for routine tests and partly as a reference instrument; routine checks are also made by connecting an ordinary three-watt 110-volt neon lamp, with resistor in base removed, between arrester ground lead and ground. The tube glows brightly for currents greater than about 250 microamperes. Company 25 employs a neon tube in a somewhat different manner; it is connected across an 0.45-megohm resistor inserted in the arrester test circuit and glows at a critical voltage of 90 volts, corresponding to a leakage current of 200 microamperes. Company 13 uses a cathode-ray oscilloscope coupled to the circuit as a milliammeter, with minimum indication at about one milliampere.

For the five companies using microammeters, four reject used arresters if leakage current at rated arrester voltage exceeds 150 microamperes—one of these (number 9) is considering a lower value for future use; the fifth company (number 16) has an upper limit of 50 microamperes for arresters. One of the four companies using 150 microamperes as a general limit (number 17) accepts one type of arrester conditionally if leakage current is between 150 and 500 microamperes, and is tagging such arresters for future identification. Company 11 has found that serious corrosion exists in this same type of arrester only where leakage currents exceeded 300 microamperes, and is conducting more inspections to establish a separate limit for this type, to supplement the 150-microampere limit for some other arresters.

Limits set by companies using milliammeters are usually minimum readable current values, which correspond to several hundred microamperes for company 10, about 250 microamperes for company 21, and about one milliampere for company 22. Companies 13 and 25, using special methods as mentioned above, have limits of about one milliampere and 200 microamperes, respectively. All limits refer to tests at rated arrester voltage, except those for company 22, which tests 9- and 15-kv arresters at rated voltage, 3-kv arresters at 4 kv, and 6-kv arresters at 5 kv, and for company 25, which tests 3-kv arresters at 2.4 kv and 12-kv arresters at 8 kv.

Six companies, three using the 150-microampere limit, gave data on rejections in this test. The rejections ranged from 5.3 to 16 per cent. The average rejections for limiting leakage currents of 50, 150, several hundred, and 1,000 microamperes were 14, 9.6, 16, and 5.3 per cent, respectively.

Dissections of arresters rejected in this test by eight companies showed corrosion of gap assemblies in most cases. Damaged gap assemblies were reported in some cases by two of these companies, and one company occasionally finds foreign particles in the gap assembly.

Test limits were set up by these eight companies on the basis of conditions found in dissecting arresters after test. Company 16 found that with leakage currents just above 50 microamperes many arresters showed corrosion, and practically all were corroded which had more than 100 microamperes leakage. Company 17 found that the limit of 150 microamperes at three-fourths of rated voltage (this limit now applying to tests at rated voltage) resulted in rejections of no arresters in good condition, about two-thirds of those with slight corrosion, and all badly corroded arresters. This is shown in figure 1 of reference 1. Company 23 supplied data for eight dissected arresters having leakage currents ranging from 155 to 400 microamperes which showed corrosion in each case. Arresters dissected by company 10 for a readable milliammeter value (several hundred microamperes) showed some defects in all cases.

Since these tests, with the two exceptions noted, are made at the rated voltage of the arrester, limiting leakage-current values appear to be about the same for different voltage ratings.

Tests on one type of arrester by com-

pany 17 have shown that 60-cycle breakdown and leakage-current measurements are practically independent of ordinary variations in ambient temperature, and that test results are reasonably reproducible over a period of several months after removing the arrester from the system.

In summary, the leakage-current test, used in conjunction with the 60-cycle breakdown test, has been used successfully by a number of utilities as a means of weeding out arresters unfit for further service.

Megger Test

Megger tests or other resistance measurements have been used by six utilities for one to five years. A 500-volt Megger is used by company 29, 1,000-volt Meggers by companies 3 and 9, and company 15 uses a 2,500-volt Megger; the Megger voltage is not stated by company 7. Company 20 uses a 12,000-megohm bridge. Limits are set at the following minimum values: company 15, 25 megohms; company 29, 100 megohms; company 20, 1,000 megohms; company 3, infinity. This is the only test used by companies 3 and 29. Companies 7 and 9 give no limits. One other company (number 13), which makes no routine Megger tests, considers this test helpful as an auxiliary check, if low enough limits are used.

The four companies having limits of 25, 100, 1,000, and infinity megohms report rejections in this test as 9.8, less than 5, 1.5, and 58 per cent, respectively. The use of the infinity limit by the latter company appears to be the cause of the unusually and, perhaps, unnecessarily high rejection rate. The 1,000-megohm limit is used by company 20 merely for rapid selection of defective units, before subjecting them to other tests.

Because of the simplicity of Megger testing, it is of interest to consider how this test compares in results with measurement of 60-cycle leakage current. Company 13 considers resistances of one megohm or less a definite indication of corrosion, but states that even with values above 20 megohms corrosion may be present. It is to be noted that the limits in use are all above 20 megohms. Data presented by company 15, covering dissections of 92 arresters, showed that the 25-megohm limit resulted in the rejection of all badly corroded and most of the moderately corroded units. Only 15 per cent of the arresters with slight corrosion and 7 per cent of those in good condition had Megger readings which would have resulted in their rejection. Company 29 found either corrosion or dust from the valve material in the gap assemblies of practically all arresters rejected in this test. Company 7 found no corrosion in arresters having Megger readings of 2,000 megohms or more, but reported one arrester with zero Megger reading which was badly corroded, and one reading 200 megohms where the gap chamber contained a web-like fungus growth.

Another company, number 9, gave corresponding 60-cycle leakage current and Megger data on over 400 arresters. A fair relationship is shown by these data, which on analysis indicate that corrosion conditions could be detected about equally well either by the 150-microampere maximum in the 60-cycle leakage current test or by a minimum of about 25 megohms in the Megger test. This company stated, however, that it is still unable to set up definite limits within which Megger readings should fall to give an accurate indication of the internal condition of the arrester, but that in the absence of other test facilities in the field the Megger is of some value in detecting moisture. They are considering a survey by Megger test of all arresters at 13.2-kv substations.

An arrester manufacturer who has conducted numerous tests on used arresters returned to the factory reports that no correlation has been found between Megger readings and arrester condition or ability to perform properly. This manufacturer prefers the 60-cycle leakage-current test, which, however, it does not consider infallible.

Considering each test by itself, then the Megger test is the simpler of the two methods. Where 60-cycle breakdown tests, however, are made, the leakage-current measurement, which appears to be the more positive test, is to be preferred, since little additional testing equipment is required. When, as, and if tests on installed arresters become advisable, the use of only the simple Megger test may be attractive.

Radio-Interference and Ionization Tests

Such tests are made by 12 companies, including two companies (numbers 13 and 16) who make ionization tests. The functions of the two tests are essentially the same, that is, to detect high-frequency oscillations set up by corona discharge within the arrester.

Radio-interference tests are made by the five utilities who described their test method by merely operating a sensitive radio set near the energized arresters. One company (number 1) mentions a separation of eight feet between the arrester and radio set antenna. Perhaps the test conditions are unnecessarily severe since arresters in service are usually relatively far from customers' equipment.

Company 8 uses a portable battery-fed receiver with a milliampere meter added to the output circuit, but ordinarily, as with the other four companies, depends on the noise from the loud-speaker. A sixth company (number 20) also uses a conventional broadcast receiver, but coupled to the primary lead of the arrester test circuit through a tuned coil and shielded lead.

Ionization tests, as used by companies 13 and 16, employ a cathode-ray oscilloscope either coupled to the arrester circuit through an air-core transformer or connected across a series inductance inserted directly in the circuit. Arresters are rejected in this test if high-frequency oscillations appear on the oscilloscope screen when the arrester is energized at the rated 60-cycle voltage of the arrester (company 13) or 1.33 times the arrester rating (company 16).

In order to pass the radio interference test, no radio noise must be noted when the arrester is energized at operating voltage (company 8), operating voltage plus one kilovolt (company 6), rated arrester voltage (companies 5, 24, and 26), or 0.83 to one times rated voltage (company 9). Company 20 tests at rated arrester voltage for arresters having Megger readings more than 1,000 megohms and at 1.33 times rated voltage for those showing less than 1,000 megohms. Company 1 applies eight kilovolts between arrester and mounting bracket in this test for both three- and nine-kilovolt arresters. The test voltage was not stated by two companies.

Arresters which fail to pass the radio-interference test of company 6, but which appear otherwise satisfactory, are dried out in an oven at about 70 degrees centigrade for 36 hours and then retested. About half of these arresters are reclaimed by this procedure. Company 17 made a trial of a similar procedure and found considerable reduction in 60-cycle leakage current for only those arresters which had visible cracks in the sealing compound; hence, it was concluded that this improvement was not likely to be permanent.

Rejections in this test, for six of the companies, ranged from 0.5 to about 11 per cent, with an average of about 3.8 per cent of arresters tested. Four companies report that arresters thus rejected show, on dissection, corroded or damp

gap assemblies or loose gap structures.

Some data are given for one of the largest urban systems, which indicate that radio-interference troubles due to faulty arresters may be too few to warrant this type of test. Field investigation of 543 complaints of radio interference during the past six years showed that the utility's equipment was responsible in only $12^1/_2$ per cent of the cases, and that only ten or 1.8 per cent of all complaints could be traced to faulty arresters. This particular company does not test arresters for radio interference.

Radio-interference or ionization tests appear desirable as a means of reducing radio interference caused by arresters on distribution systems only where this trouble exists to a serious extent. Where such tests are made to determine radio-interference levels likely to cause complaints in service, the method described in EEI Publication No. *C*-9, "Methods of Measuring Radio Noise," is recommended.

Leakage Over Porcelain

Company 21 includes in its routine tests on new and used arresters a test for "leakage over porcelain." Twice rated 60-cycle arrester voltage plus 1,000 volts (except three-kilovolt arresters, which are tested at 10 kilovolts) is applied between the line lead and hanger bracket, and leakage current over the arrester body measured with a milliammeter. The maximum permissible leakage current is five milliamperes. No data were given to correlate test results with arrester conditions.

Tests on New Arresters

As shown in table I, routine tests on new arresters are made by six companies: three (numbers 21, 25, and 26) testing all new arresters, two (numbers 8 and 16) ten per cent of arresters purchased, and one (number 18) three arresters of each rating from every shipment received. Tests are made in the same manner as the tests previously described for arresters removed from service. The test limits are the same as for used arresters for these companies, except that company 16 has a 30-microampere limit in the 60-cycle leakage test.

Data regarding rejections of new arresters on routine tests were supplied by companies 8 and 26, reporting no rejections in more than 10,000 tests, and by company 16, which rejected two arresters out of 195 (representing 1,950 arresters purchased). Company 17, which no longer tests new arresters except for new designs, in earlier tests on 2,200 new arresters rejected very few by test.

These practices and results indicate that routine testing of new arresters by the purchaser may be difficult to justify. Tests on new designs and occasional check tests on representative arresters purchased, however, may be of value.

Tests on Arresters in Service

Radio interference tests are made in the field by company 7 on installed three-kilovolt arresters, incidental to this company's general investigations of radio interference complaints. Measurements are made with a portable radio set, the output of which is determined using an attenuation box. The detection of defective arresters is often aided by jarring the pole with a sledge hammer, but positive localization requires disconnecting the arrester from the line during noise level measurements.

Interference from arresters was reported to be caused most often by moisture and corrosion in the gap chamber. Of approximately 1,000 arresters checked in the field each year for radio interference since 1924, about 100 arresters have been removed annually and scrapped.

Test Combinations in Use

As shown in table I, testing procedures in use generally include more than one type of test, each test as a rule serving to detect specific types of defects. The most usual combinations, where all types of tests are considered, include: 60-cycle breakdown and leakage current (five companies); 60-cycle withstand and radio interference (five companies); and 60-cycle withstand alone (four companies). Excluding impulse, radio interference, and ionization tests, the most common combinations are: 60-cycle withstand alone (ten companies); 60-cycle breakdown and leakage current (seven companies); and 60-cycle breakdown alone (four companies).

Economics of Arrester Testing

Data on the costs of testing and rehabilitating arresters removed from service, as given by 14 companies, are included in table I. Two cost figures are shown: the testing cost per arrester exclusive of fixed and maintenance charges of the testing equipment, and the cost of tests and repairs per arrester returned to stock. The latter figure includes the cost of work on arresters which were found unsuitable for re-use, prorated as to each arrester accepted.

Testing costs range from 4 to nearly 75 cents, averaging about 29 cents per arrester tested. These costs apparently vary widely with local conditions, since they bear no relation to the number or types of tests made.

Total costs per arrester found to be in condition suitable for re-use range from about 20 cents to $2.00, and average about 83 cents. These costs vary widely due to local conditions as well as to the amount of repair work done. Company 6, reporting a total cost of $1.10 per arrester, replaces broken leads and caps and bakes out those arresters which initially fail to pass the radio-interference test. The total cost of $1.30 to $1.40 per arrester given by company 12 includes increasing the length of the line lead in all cases. Costs for neutral gaps are given as 69 cents by company 17, as compared with $1.12 for three-kilovolt phase arresters, the difference resulting from less repair work required.

Costs for testing and rehabilitating arresters of different voltage ratings are reported to be essentially independent of rating by companies 1, 5, 12, and 15.

The average cost of testing and rehabilitating arresters for re-use amounts to between 5 and 15 per cent of the new arrester cost, for ratings of 3 to 15 kv. Assuming that the useful life of the rehabilitated arrester is equal to one-half of the life of arresters now made, then, for example, there appears to be a saving of the order of 65 per cent in re-using 3-kv arresters after thorough test, over the cost of replacement with new arresters. For higher voltage ratings the economic advantage of testing arresters is more pronounced.

General Summary for Used Arresters

A summary of the test methods in use, together with conditions and defects indicated by each test, is given below for purposes of comparison:

(*a*). *Impulse Tests*. Impulse characteristics; ability to interrupt follow current.

(*b*). *Sixty-Cycle Withstand*. Following to a serious extent: corrosion; damaged gaps or valve elements; foreign particles in gap.

(*c*). *Sixty-Cycle Breakdown*. Pitted, burned, or corroded gaps; broken springs; foreign particles in gap; damaged or wet valve element.

(*d*). *Sixty-Cycle Leakage*. Corrosion; other conditions to a limited degree.

(*e*). *Megger*. Corrosion; other conditions to a limited degree.

(*f*). *Radio Interference or Ionization.* Conditions, such as corrosion or loose contacts, causing radio interference.

Test method (*a*) serves the purpose of checking the protective characteristics of the arrester, while the other methods are used to determine the physical conditions of the arrester as affecting the expected electrical characteristics in future service. Test methods (*b*) and (*c*) serve somewhat the same purpose, although method (*b*), the simpler test, is less effective than method (*c*). Likewise, methods (*d*) and (*e*) are similar in objectives; test (*e*) is relatively simple and inexpensive, but not proved as reliable; method (*d*), however, may be readily combined with test method (*c*), where used, and may be more successful under usual conditions.

In general, testing costs represent a small proportion of the costs of restocking good used arresters, and so differences between costs of tests may be unimportant. This is, of course, only true where sufficient arresters are to be tested to justify initial costs of testing equipment.

Suggestions for Testing Used Arresters

For routine tests on arresters removed from service, suggested combinations of tests which have been found to be simple and effective, and which require little complicated or expensive apparatus are as follows:

1. Sixty-cycle breakdown and leakage current measurements.
2. Sixty-cycle breakdown and Megger tests.
3. Sixty-cycle withstand and leakage current (or Megger) tests.

In conjunction with any of these test combinations, radio interference or ionization tests may be used, where such testing is warranted by local radio-interference conditions. Also, occasional or routine impulse tests may be made on used arresters where suitable equipment is available.

Based on present practice and results of tests in use, test limits suggested for trial use by utilities starting routine testing of arresters returned from service are given below:

Impulse Test. Use reference 2 as a general guide for voltage limits, but modify them in accordance with testing experience with used arresters.

Sixty-Cycle Withstand. Test at 1.0 or $1^1/_4$ times rated arrester voltage.

Sixty-Cycle Breakdown. Acceptable voltage range: $1^1/_3$ to 3 or 4 times rated arrester voltage.

Sixty-Cycle Leakage Current. Maximum at rated arrester voltage; 150 microamperes or lowest reading on milliammeter scale.

Megger. Minimum: 25 megohms. Preferable to use 1,000- or 2,500-volt Megger.

Radio Interference. Test at rated arrester voltage.

These values should be considered as tentative and should be modified as found necessary to meet individual conditions after the testing program has been started and a number of arresters, which on test show values both above and below the trial limits, have been dissected.

References

1. Testing and Application of Lightning Arresters, AIEE Lightning Arrester Subcommittee Report. AIEE Transactions, 1939, page 68 (February section).

2. Distribution Lightning Arrester Performance Data, AIEE Lightning Arrester Subcommittee Report. Electrical Engineering (AIEE Transactions), volume 56, 1937, page 576.

Discussion

E. J. Allen (General Electric Company, Pittsfield, Mass.): The replies from 29 companies now engaged in the testing of distribution lightning arresters have been well analyzed and presented. In view of the diversity of methods employed by the different companies making the six classifications of tests shown on table I, it would be of interest to determine what reasons govern the particular choice of some of the tests and what they were intended to demonstrate. In the best interests of uniform interpretation of data obtained from testing of distribution arresters, it is obvious that uniformity in test methods need be followed.

Our experience as a manufacturer with new and used arresters has demonstrated that the already prescribed test which most nearly approaches actual service conditions is the "operating duty test" set forth in AIEE Standards No. 28, issue of March 1936. As the three companies making impulse tests on arresters apparently do so with combined power voltage, the term "impulse test" applying to these companies and used by the author would preferably be extended to the term "operating duty test" as designated in the Standards. This distinction is made, since without the combined power voltage there is no indication of the arrester's ability to interrupt follow current.

Contrary to the practice described by one company, the AIEE Standards do not specify that the power voltage applied to the arrester during the operating duty test shall be in excess of maximum arrester rating, as this is not a condition for which the arrester was designed. The operating duty test on three-kilovolt arresters with four-kilovolt power voltage applied, may result in unnecessary damage to the arresters and hence should be discontinued.

Notwithstanding the fact that the AIEE Standards "operating duty test" describe a single test that will probably tell the most about the operating condition of a lightning arrester, simpler tests have been sought for use either in the laboratory or field, that would be equally indicative. The 60-cycle spark potential, 60-cycle withstand voltage, leakage current, Megger, or resistance bridge tests are examples which are described in the paper and which are used the most in the order just stated. Since these tests are only partially indicative of the operating condition of the arrester, they are subject to the following limitations:

Sixty-Cycle Spark Potential Test

(*a*). The most that this test might be expected to show is either a short-circuited arrester or an open-circuited arrester.

(*b*). This test will not necessarily show a damaged valve element, presence of moisture, or otherwise disclose the valve or resealing characteristics of the arrester. It is not an indication of the impulse protective characteristics of the arrester or suitability of the arrester for further service.

(*c*). Unless extreme precautions are observed, either or both of the gap and valve elements in good arresters may be damaged and unless the results are intelligently analyzed, good arresters may be unnecessarily rejected. Since this test subjects the valve element to 60-cycle voltage in excess of its rating, tests should be limited to not more than three applications and spark-potential reading.

Sixty-Cycle Withstand Test

(*a*). This test will indicate only a short-circuited arrester. As the author points out, it should not be considered an infallible test for defects and should be used in conjunction with other tests.

(*b*). The power voltage applied should preferably not be in excess of the maximum arrester rating. If the applied voltage is 1.25 times maximum arrester rating, as suggested in the paper, care should be taken to avoid sparking over the arrester gap by switching surges incidental to the test, as such spark-over of the gap could destroy the arrester by application of power voltage above the arrester's maximum valve or resealing rating.

Leakage Current, Resistance Bridge, or Megger Test

(*a*). The most that this test might be expected to indicate is the possible presence of moisture or corrosion in the arrester elements that may or may not be injurious to the service operation of the arrester.

(*b*). This test will not necessarily differentiate between leakage current caused by external moisture, humidity or surface deposits, as against leakage currents caused by moisture or corrosion of internal elements. This test will not show an open-circuited arrester, damaged valve elements, or the protective characteristics of the arrester.

(*c*). While the leakage current measured at no greater applied voltage than maximum arrester rating would not be likely to damage it in any way, precautions are necessary to assure that the applied power voltage never exceeds the maximum rating.

(*d*). As the author mentions, the 60-cycle leakage-current test at maximum arrester voltage rating is to be preferred as compared with the resistance bridge or Megger.

Hence, the simpler tests which show the operating condition of a lightning arrester only to a partial extent should not be taken in themselves as definite cause for arrester rejection. Such arresters might give many years of continued reliable protection.

The author's statement that there seems to be little need for tests on new arresters by the operating company is borne out in table I of the paper in which virtually no new arresters are rejected by any of the testing methods described in the paper.

Cost data has been included covering testing and repairing by the companies reporting. The average testing and rehabilitating cost per arrester returned to stock of $0.83 apparently covers only minor re-

The Direct-Acting Generator Voltage Regulator

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Synopsis: The principal factors involved in the design and application of direct-acting voltage regulators and their relations to each other are discussed in this paper. The mathematical method used for deriving these relations is outlined. Definite conclusions are drawn concerning proper operation and design of this type of regulator.

In recent years increasingly wide use has been made of direct-acting voltage regulators. During this time, improvements in design and a better understanding of their characteristics have developed. This paper describes some of the improvements and presents a mathematical analysis of a regulating system including a generator and exciter with a voltage regulator. It will be seen that many of the improvements in design follow directly and logically from the results of the mathematical analysis.

Improvements in Design and Operation

The first requirement of a regulating device is that it hold the regulated voltage very closely to the desired value without hunting or instability. Its ability to do this is influenced by all the elements of the system, including the generator and its load, the exciter, and the voltage regulator. Therefore, in order to understand the factors involved it is necessary to study the system as well as the regulator itself. It has been found that essentially perfect regulation can be maintained by the modern regulator over a wide range of operating conditions with stability. This performance is achieved by utilizing an inherent nonlinear property of the resistance elements, by careful balancing of the electrical and spring torques at every point in the range, and by use of a stabilizing transformer.

The second important requirement of a regulator is that it make the necessary changes to return the voltage to normal as quickly as possible after any sudden change in the operating condition. The time for voltage recovery is also affected by the other parts of the system. All that the regulator can do is to go immediately to its extreme position for raising or lowering the voltage, and then as the voltage approaches normal, fall back in such a way as to prevent excessive overswing. The extent to which the modern regulator approaches this ideal is shown by the oscillogram in figure 1. Notice that the regulator resistance becomes zero in less than two cycles, or about $^1/_{30}$ second after the load change occurs. This rapid response is made possible by new materials and a superior mechanical design which permit reduction of the inertia of the moving parts and of the inductance of the regulator coil.

A third requirement of any regulating mechanism, and by no means the least important, is that it be simple and highly reliable, and that it require a minimum of maintenance. Figures 2 and 3 show that these considerations have also had their part in the evolution of the modern regulator.

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For their assistance in the preparation of this paper, the authors are especially indebted to R. W. Porter and C. Concordia.

Regulating System Assumed for Analysis

Figure 4 is a schematic drawing of the regulator and a connection diagram for the typical regulating system which is analyzed in this paper. The regulator operates by controlling the resistance in the shunt field circuit of the exciter in the following manner: The resistance presented by the regulator elements is varied in response to movement of the regulator armature. The position of the armature is determined by the balance between the torque of the spring and the electrical torque of the magnet. The current in the magnet coil comes from the a-c generator voltage through a rectifier. If the voltage drops, the current in the coil decreases, the armature changes position, and lowers the resistance in the exciter field until the voltage comes back to normal. The stabilizer, a simple iron-core transformer with an air gap, impresses in the regulator-coil circuit a transient voltage depending upon the change in generator field voltage. This transient voltage makes the regulator anticipate slightly the return of the alternating voltage to normal and thereby decreases the tendency to overswing or hunt.

Method of Analysis

The tensor method of analysis, which is particularly well adapted for problems

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pairs, as for example replacement of broken leads and caps to which reference is made in the paper.

The return on the investment in testing, and economic justification for such expenditure is probably questionable at least until the reliability of the testing methods is better established, and the loss of possible further years of service from unnecessarily rejected arresters is fully evaluated. The economic justification would also be questionable if repetitions of tests and cumulative expense for removals from service and testing over frequent intervals were necessary on the same arrester. More lasting economies would favor substitution by new arresters of modern design.

Herman Halperin: E. J. Allen has presented a critical discussion which should be stimulating to those interested in testing distribution arresters. Part of his remarks reiterate points made in the paper on shortcomings of the various simple tests in use, but in some places the criticism seems unwarranted and unsubstantiated by the experiences of utilities who have conducted tests. It is not certain that even the operating-duty test, which he emphasizes as all-important, will always eliminate an arrester which is in questionable physical condition. Detailed dissection of used arresters by utilities has disclosed a general correlation between observations and results of the tests which are made inexpensively with relatively simple apparatus. As to damage to the arresters by repeated 60-cycle tests, which should not occur with properly designed test circuits, the practices of utilities should not usually result in a given arrester's being installed and removed more than twice. The increasing number of utilities which find it desirable to test used arresters appears to justify the economic value of that practice. Further service experience with used arresters which were tested will be of immediate interest.

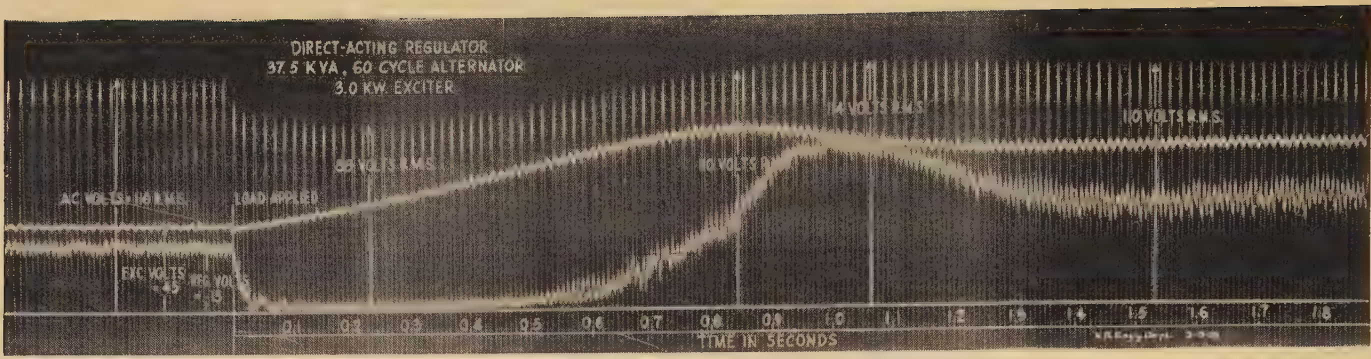


Figure 1. Oscillogram showing response of direct-acting regulator

"Exc. Volts" is measured across the exciter armature

"Reg. Volts" is measured across the regulator rheostat

Alternator originally at no load; 19.0 kva, 0.3 power factor load applied

involving many elements, was used to set up the differential equations for small variations in the voltages, currents, torques, and angles of the regulating system. These equations were then examined to determine whether or not the variations tend to die away after a slight disturbance or to become larger with increasing time. In stable systems, the variations caused by any slight disturbance diminish to zero. But if any of the variations have a tendency to become larger, the system will not be in stable equilibrium at the operating point in question. This unstable condition is manifested by continued hunting or oscillating.

Any tendency for the variations to increase is evidenced by the existence of a positive real part in one or more of the roots of the characteristic denominator of the differential equations. Such a positive real part may be detected by the use of Routh's criterion.[1] In this manner regions of stable and unstable equilibrium were determined and factors which make for stability or instability investigated quantitatively.

General Conclusions

The more important results of this analysis can be briefly summarized as follows: It was found, for the typical system studied, that

1. In order to improve regulation

(*a*). The rate of change of regulator stack resistance with change in displacement should be large.

(*b*). The rate of change of regulator electrical torque with change in coil current should be large.

(*c*). The difference between the rates of change of electrical torque and of mechanical torque with respect to regulator-armature mechanical displacement should be small.

(*d*). The difference between the rates of change of exciter armature voltage and of exciter field circuit IR drop with respect to exciter field current should be small.

(*e*). The rate of change of regulator stack resistance with change in current should be negative.

2. In order to improve the stability

(*a*). The factors listed in conclusion 1 should be changed in the opposite direction to that required for improving the regulation.

(*b*). The moment of inertia of all the movable parts of the regulator should be reduced.

(*c*). The exciter field inductance should be increased.

3. With reduction in the moment of inertia, the factors which influence the regulation have less influence on the stability; therefore they can be changed in the direction to improve the regulation without impairing the stability as much as would be the case with a higher moment of inertia.

4. In the region of low exciter saturation, perfect regulation, or even a slightly rising voltage characteristic with load can be obtained with stability.

The analytical results are in agreement with present laboratory and field experience. Accordingly the method presented is a dependable means by which the effects of the various influencing factors on a regulating system may be analyzed and knowledge of regulating systems be extended.

Discussion

Grouping of Constants

In analyzing the regulating system it was possible to group many of the circuit constants together in order to simplify the analysis and help provide a clear physical concept. Two important factors in the operation of the system, both from a stability and regulation standpoint, are designated by the terms R_D and X_D, which have been called exciter stability factor and regulator stability factor, respectively.

R_D is the difference between the effective resistance of the exciter field circuit to small current changes, and the ratio of the change in generated voltage of the exciter to the corresponding small change in exciter field current. Referring to figure 5, OS is the exciter saturation curve measuring the variation of exciter generated voltage with field current, and the line OA is the exciter-field-circuit resistance line for a particular position of the regulator. The curvature of this line comes from the nonlinear characteristic of the resistance used in the regulator. The line ss' is tangent to the curve OS at the operating point P; aa' is tangent to the curve OA. The greater the difference between the slopes of aa' and ss', the less susceptible the exciter voltage is to slight changes in resistance. Accordingly, the difference of these slopes can be considered as a measure of the stability of the exciter. Such a concept is well-known.

The characteristic of the regulator resistance is such that its effective resistance decreases with increase in current. As shown by figure 5, this characteristic tends to make curve OA ap-

Figure 2. Direct-acting voltage regulator with enclosing case

1. For all numbered references, see list at end of paper.

proach OS in shape thereby reducing the difference between the slopes of aa' and ss', and making this difference more uniform over the operating range. If the resistance curve is sufficiently nonlinear, the difference of the slopes may be slightly negative, $-R_D$. Although the exciter by itself may be unstable under this condition, the corrective action of the regulator and stabilizer can overcome this instability and produce stable operation of the system. In fact, a uniformly low or negative value of R_D is desirable as a means of improving the regulation.

X_D, the regulator stability factor, is the difference between the rate of change of spring torque acting on the regulator armature and the corresponding rate of change of electrical torque for a given small change in mechanical displacement. See figure 6.

If the regulator armature is to be at equilibrium in any particular position, the electrical torque must just overcome the spring torque at that position. Now if the armature is moved by some external torque in the same direction as the magnetic torque, the spring will be further stressed and its force will increase slightly. Even though the alternating voltage from which the coil is magnetized remains constant during this process, the magnetic force may increase or decrease depending on the shape of the armature and pole tips. If the magnetic force decreases, or, as

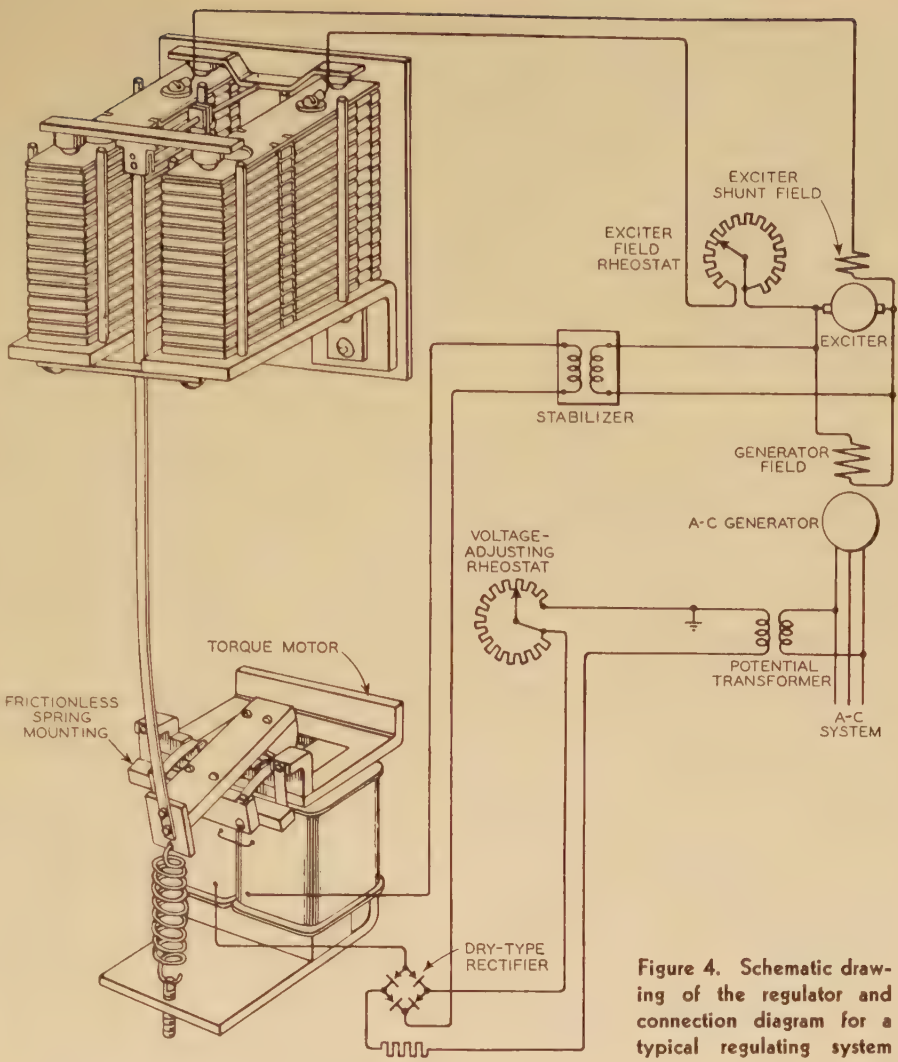


Figure 4. Schematic drawing of the regulator and connection diagram for a typical regulating system

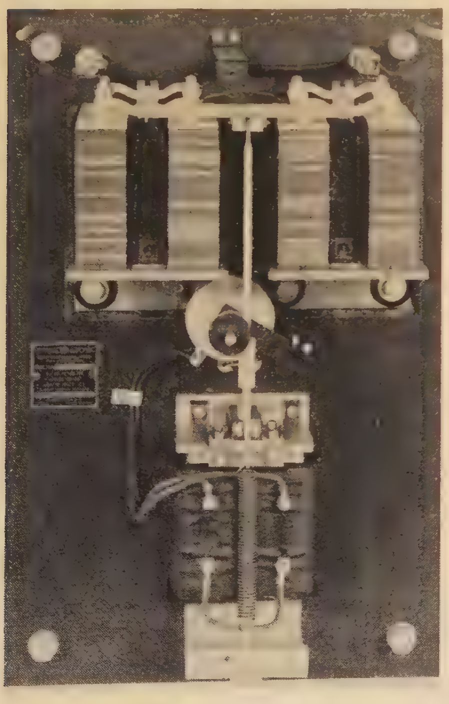


Figure 3. Direct-acting voltage regulator with enclosing case removed, showing operating mechanism

in figure 6, increases less rapidly than the opposing spring force, the armature will be urged back to its initial position. Such an equilibrium is commonly called stable equilibrium. But if the magnetic force increases more rapidly than the spring force, the armature will be urged away from its initial position, and the operating point will be a point of unstable equilibrium. Thus X_D, the difference between the rate of increase of the spring torque and of the electrical torque, is a measure of the stability of the regulator armature.

The more positive this quantity, X_D, becomes, the less sensitive the armature will be to a given change in electrical torque. Therefore X_D is inversely proportional to the amplification of the mechanical part of the regulator just as R_D is inversely proportional to the amplification of the exciter.

Regulation

The regulation of a system, which is a measure of its ability to hold the regulated quantity at a constant value, is a function of what has been termed in the analysis the over-all amplification factor. This factor can be defined as the ratio of the change in the terminal voltage of the a-c machine to an arbitrary small change in the alternating voltage applied to the regulator. It normally has a negative sign, for when the voltage applied to the regulator is high, the regulator tends to reduce the alternator terminal voltage.

The total amplification factor of the system is the product of the amplification factors of the various elements which may be considered as constituting stages of amplification. This is readily visualized by consideration of figure 7 which shows schematically the different elements of the system as stages of amplification and the corresponding mathematical expressions which define their respective amplification factors.

The amplification may be very large, theoretically equal to infinity, if either the regulator stability factor, X_D, or the exciter stability factor, R_D, are equal to zero. This indicates that flat regulation can be obtained if the exciter or regulator is operated at a point where

it would approach instability by itself. The amplification factor may even be a positive number, which corresponds to a rise in voltage with increase in load, if either R_D or X_D is negative. Whether it is positive or negative, the amplification factor is increased in magnitude by increasing the rate of change of regulator stack resistance with armature mechanical displacement, or by increasing the rate of change of electrical torque with regulator-coil current.

Stability

The regulator and exciter stability factors, R_D and X_D, are two of the most important factors which influence stability. They are also the two which can be varied most easily. For this reason, they were chosen as ordinates for the curves which show the results of the stability analysis.

Figure 8 shows the effect of a stabilizer for a typical set of conditions with the regulator moment of inertia neglected (assumed equal to zero). The abscissa is X_D, the regulator stability factor; the ordinate is R_D, the exciter stability factor. Curve A shows that over-all stable operation will exist without a stabilizer in the region of low exciter stability if X_D is large. However, as R_D can be expected to vary appreciably with exciter saturation over the range of loads and with field temperature, good over-all regulation must be obtained by making X_D small also. Curve B shows that if a stabilizer is used, stable operation can be maintained with small values of both X_D and R_D. Thus the effect of the stabilizer is clearly shown in compensating for regulator instability and in making possible good regulation with stable operation over the range which R_D may take. By design practice, the operating point is kept well within the stable regions in order that all oscillations will decay rapidly.

The effect of variation in the regulator moment of inertia is shown in figure 9, other conditions remaining the same as for figure 8, curve B. These curves show very clearly that the smaller the moment of inertia of the regulator, the greater the stability. As the moment of inertia does not affect the regulation, it should be made as small as possible. By so doing improved regulation can be obtained, without instability.

Figure 10 shows the effect on stability when the rate of change of regulator resistance with armature displacement is increased four times for a given set of conditions. This comparison shows that from the viewpoint of stability alone it appears desirable to make the rate of change small. Notice, however, that a given increase in the rate of change does not require a proportional increase in X_D for stability. On the other hand, the amplification factor, which determines the regulation, is directly proportional to the ratio of the rate of change of resistance to X_D. Therefore, a net improvement in regulation can be obtained without affecting the stability by increasing both the rate of change of regulator resistance with displacement and the value of X_D.

Figure 11 shows the effect of changing the exciter-field inductance, all other factors remaining the same. These curves indicate that a system is more likely to be stable if the exciter-field time constant is large, but this condition is contrary to the requirement of rapid response. Consequently, increase of exciter-field time constant is not in general a practical method for improving stability.

Analysis

Assumptions

In order to adapt this investigation to mathematical analysis certain assumptions were made, the most important of which are the following:

1. Displacements are of small magnitude.
2. The alternator speed is constant.
3. The alternator load is purely reactive. Reactive loads usually cause the most severe regulation.
4. Voltages due to rates of change of flux linkages are small compared to voltages due to rotation of the machine.
5. The exciter speed is constant.
6. Friction in the movable parts of the regulator is negligible. Friction is kept as small as possible on most regulators for mechanical reasons.
7. At the operating point the rectifier develops changes in direct voltage proportional to changes in the fundamental alternating voltage less a linear resistance drop.

Both regulation and stability were studied on the basis of the above assumptions. This work indicated that it was reasonable to make further assumptions in the study of stability. These further assumptions were:

1. The alternator is at no load.
2. Stabilizer magnetizing current is negligible.

Figure 7. Stages of amplification and over-all amplification factor

$$\mu_o = \frac{\mu_r\left(\frac{\partial T_e}{\partial i^m}\right)\left(\frac{\partial r_h}{\partial \theta^\theta} i^h\right)\left(\frac{\partial E_c}{\partial i^c}\right)\left(\frac{\partial E_f}{\partial i^f}\right)}{r_k X_D R_D r_f}$$

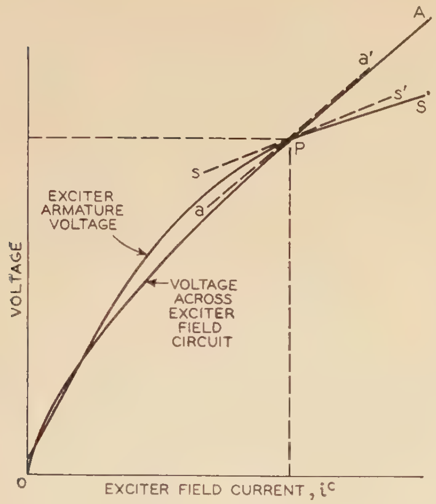
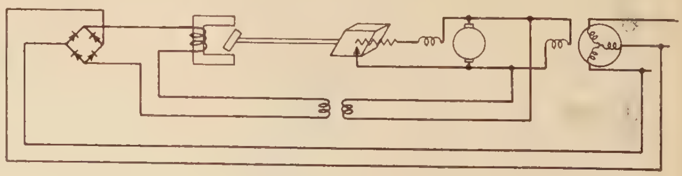


Figure 5 (left). Illustration of R_D, exciter stability factor

R_D = slope aa' minus slope ss'



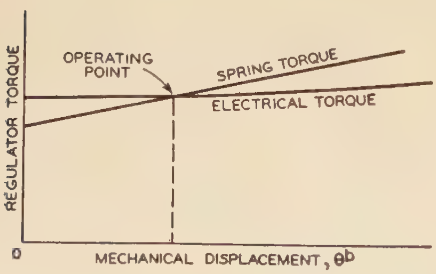
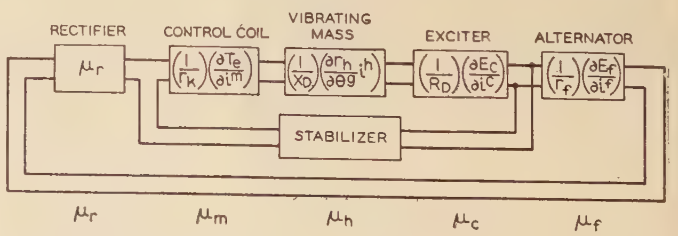


Figure 6 (left). Illustration of X_D, regulator stability factor

X_D = slope of spring torque curve minus slope of electrical torque curve



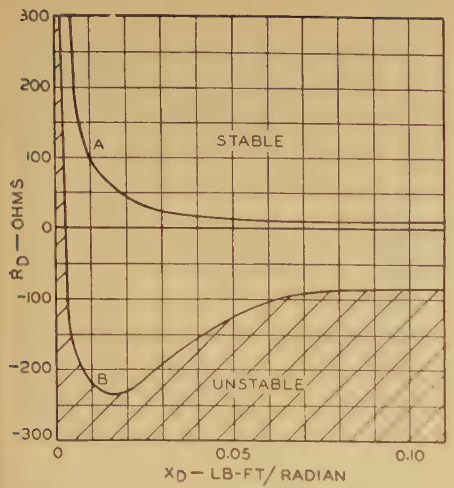


Figure 8. Excitation-system stability characteristics showing effect of stabilizer. Regulator moment of inertia neglected (assumed equal to zero)

Alternator rating 37.5 kva, 110 volts, 60 cycles

A—No stabilizer B—With stabilizer

3. Exciter armature resistance is negligible.
4. Exciter armature inductance is negligible.

The point at which these additional assumptions are introduced is indicated in the analysis.

Nomenclature

Particular values of the following quantities are identified by appropriate superscripts.

i—current
θ—angle of displacement from a given position

Particular values of the following quantities are identified by appropriate subscripts.

m—moment of inertia
e—voltage
r—resistance
ψ—flux linkages
$L = \partial\psi/\partial i$—incremental self-inductance
$M = \partial\psi/\partial i$—incremental mutual inductance
E—generated voltage due to rotation relative to flux in line with field poles
μ—amplification factor of an element of the regulating system

The following symbols are used as subscripts or superscripts.

m—regulator coil
h—regulator rheostat
b—regulator armature
g—rheostat operating arm
c—exciter field
a—exciter armature
f—alternator field
d—alternator direct axis[2]
q—alternator quadrature axis[2]
r—rectifier
p—primary of stabilizer (connected to exciter armature)
s—secondary of stabilizer (connected into regulator circuit)
k—regulator-coil circuit (rectifier, stabilizer secondary, and regulator coil) under steady-state conditions
T—regulator-coil circuit of the interconnected system under oscillatory conditions

When not identified by a subscript:

$m = m_b + m_g$ = total moment of inertia of movable parts of the regulator

The following quantities also appear in the analysis:

T_e—electrical torque on regulator armature
T_Σ—spring torque on regulator armature
μ_0—over-all amplification factor
n—ratio of $\dfrac{\text{primary turns}}{\text{secondary turns}}$ of stabilizer

It should be noted that resistances, inductances, and flux linkages of the stabilizer are referred to the primary.

$$R_D = -\frac{\partial E_c}{\partial i^c} + r_h + r_c + \frac{\partial r_h}{\partial i^h} i^c + r_a,$$

the exciter stability factor.

$$X_D = \frac{\partial T_\Sigma}{\partial \theta^b} - \frac{\partial T_e}{\partial \theta^b},$$

the regulator stability factor.

In the tensor notation, each unit vector is designated in bold-face type by the same symbol which is used as a superscript for the current (or angle) of the circuit to which the unit vector applies.

A prime (′) identifies terms applying to the system after interconnection.

A double prime (″) identifies terms applying to the interconnected system after introduction of the assumption that stabilizer magnetizing current is negligible.

Derivation of Equations

The following presents the development of the equations from which the performance of the system (figure 13) was determined. Using the tensor method of attack,[3] the first step was to set down the equations for the individual parts of the system shown in figure 12; second, by means of the connection tensor, the equations applying to the interconnected system were

Figure 9. Excitation-system stability characteristics showing effect of change in regulator moment of inertia. Effect of stabilizer included

Alternator rating 37.5 kva, 110 volts, 60 cycles

A—$m = 0$
B—$m = 7.37 \times 10^{-6}$ pound-feet-seconds²/radian
C—$m = 73.7 \times 10^{-6}$ pound-feet-seconds²/radian

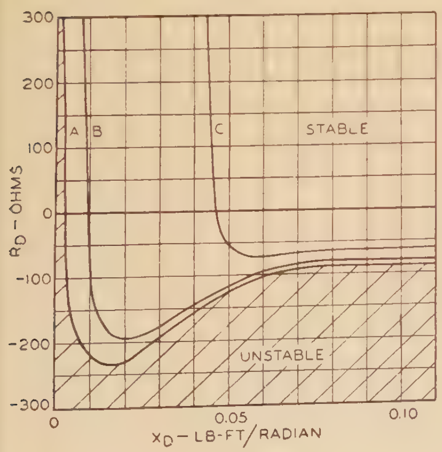


Figure 10. Excitation-system stability characteristics showing effect of change in the rate of change of regulator rheostat resistance with regulator displacement

Alternator rating 37.5 kva, 110 volts, 60 cycles

A—$\dfrac{\partial r_h}{\partial \theta^g} i^c = 40.7$ volts per radian

B—$\dfrac{\partial r_h}{\partial \theta^g} i^c = 162.5$ volts per radian

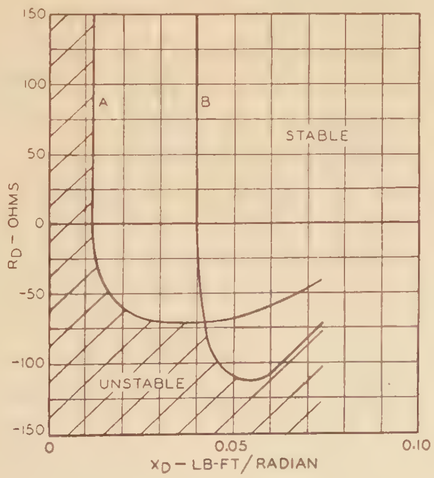
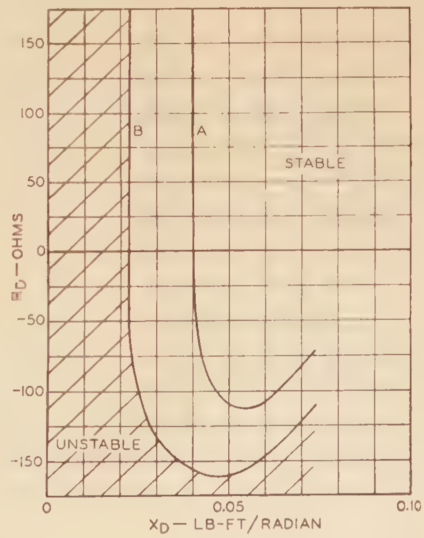


Figure 11. Excitation-system stability characteristics showing effect of change in exciter field inductance

Alternator rating 37.5 kva, 110 volts, 60 cycles

A—$L_c = 30$ henries B—$L_c = 60$ henries



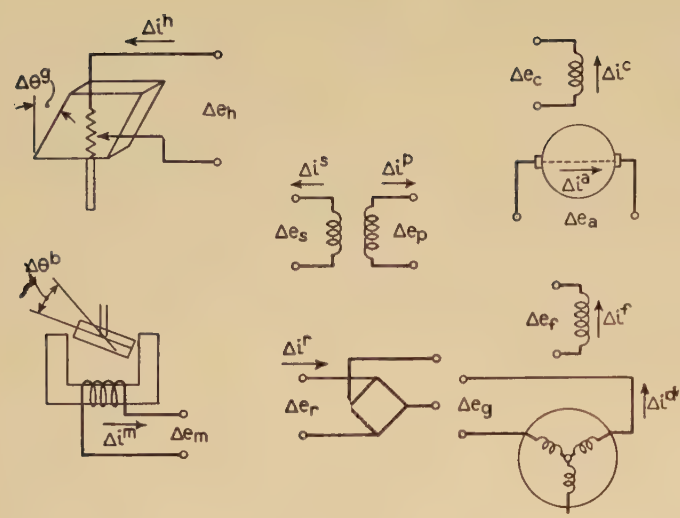


Figure 12. Component parts of regulating system before interconnection

a—Exciter armature
b—Regulator armature
c—Exciter field
d—Alternator armature
f—Alternator field
g—Rheostat operating arm
h—Regulator rheostat
m—Regulator coil
p—Stabilizer primary
r—Rectifier
s—Stabilizer secondary

found; third, the determinant of the equations for the currents and angular displacements was found; and fourth, Routh's criterion[1] was applied in order to determine the necessary conditions for stable operation. Routh's criterion is an algebraic rule, the application of which is discussed later in this analysis.

1. *General Equations Before the Interconnection*

The equations for the component parts may be summarized by the equation of small changes

$$\Delta \boldsymbol{e} = \boldsymbol{z} \cdot \Delta \boldsymbol{i} \tag{1}$$

where the impedance tensor, $\boldsymbol{z}$, of the component parts is given in equation 2.

2. *Equations for the Connected System*

When the parts are connected together as shown in figure 13, the effect of the interconnection may be represented by transformation of the tensor, $\boldsymbol{z}$, according to the equation

$$\boldsymbol{z}' = \boldsymbol{C}_t \cdot \boldsymbol{z} \cdot \boldsymbol{C} \tag{3}$$

where

$$\boldsymbol{C} = \begin{array}{c|cccccc|} & c' & f' & p' & m' & b' & d' \\ \hline m & & & & 1 & & \\ b & & & & & 1 & \\ h & 1 & & & & & \\ g & & & & & 1 & \\ c & 1 & & & & & \\ a & 1 & 1 & 1 & & & \\ f & & 1 & & & & \\ r & & & & 1 & & \\ d & & & & & & 1 \\ p & & & 1 & & & \\ s & & & & -1 & & \\ \hline \end{array} \tag{4}$$

Performance of the operations indicated in (3) yields equation 5.

3. *Regulation*

If the regulator were inoperative, a change, Δe_q, in alternator terminal voltage would not result in any change, Δi^f, in alternator field current or corresponding change $(\partial E_f/\partial i^f)\ \Delta i^f$, in internal generated voltage. The effectiveness of the regulator may be expressed in terms of its ability to cause a change $(\partial E_f/\partial i^f)\ \Delta i^f$, in response to a change, Δe_q.

At steady state ($p = 0$), solution of equation 5 yields

$$\frac{\partial E_f}{\partial i^f} \Delta i^f = \mu_0 \Delta e_q \tag{6}$$

where the steady-state amplification factor,

$$\mu_0 = \frac{-\mu_r \dfrac{\partial E_f}{\partial i^f} \cdot \dfrac{\partial T_e}{\partial i^m}\left(\dfrac{\partial E_c}{\partial i^c} - r_a\right)\dfrac{\partial r_h}{\partial \theta^g} i^c}{r_m + \ r_r + \dfrac{r_s}{n^2}\Big) X_D \left[R_D + r_a\left(1 + \dfrac{r_f}{r_p}\right) \dfrac{\dfrac{\partial E_c}{\partial i^c} - r_a}{r_f + r_a\left(1 + \dfrac{r_f}{r_p}\right)} \right] \left[r_f + r_a\left(1 + \dfrac{r_f}{r_p}\right)\right]} \tag{7}$$

For $r_a = 0$, equation 7 for the steady-state amplification factor, becomes

$$\mu_0 = -\frac{\dfrac{\partial r_h}{\partial \theta^g} i^c \dfrac{\partial T_e}{\partial i^m} \mu_r \dfrac{\partial E_f}{\partial i^f}\ \dfrac{\partial E_c}{\partial i^c}}{R_D X_D r_f r_k} \tag{8}$$

where

$$r_k = r_m + r_r + \frac{r_s}{n^2}$$

This may be written as

$$\mu_0 = -[\mu_r]\left[\left(\frac{1}{r_k}\right)\left(\frac{\partial T_e}{\partial i^m}\right)\right] \times \left[\left(\frac{1}{X_D}\right)\left(\frac{\partial r_h}{\partial \theta^g} i^c\right)\right]\left[\left(\frac{1}{R_D}\right)\left(\frac{\partial E_c}{\partial i^c}\right)\right] \times \left[\left(\frac{1}{r_f}\right)\left(\frac{\partial E_f}{\partial i^f}\right)\right] \tag{9}$$

$$= -\mu_r \mu_m \mu_h \mu_c \mu_f$$

where the μ's are the amplification factors of the various stages (see figure 7).

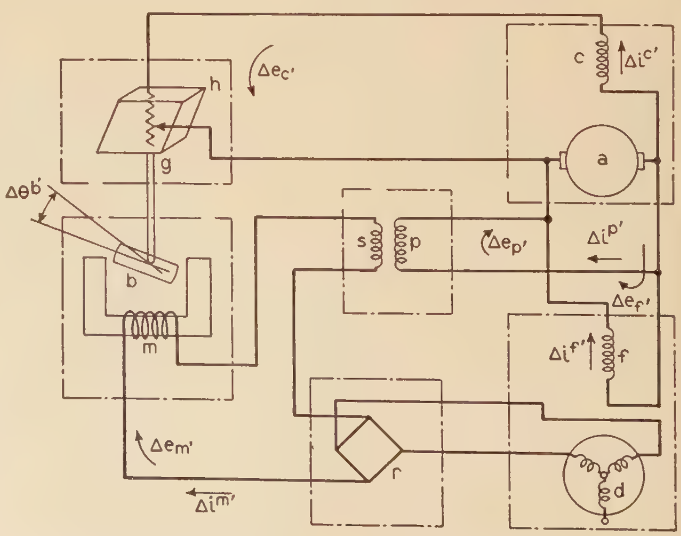
It may be seen that, in general, each amplification factor consists of a self-admittance times a mutual impedance. The effect on regulation of changes in any of the system constants can thus readily be visualized in terms of their effect on these admittances and impedances.

4. *Stability*

Equation 5 defines the system of differential equations which apply to the departures, $\Delta \boldsymbol{i}$, from steady-state values of the currents (and angle) of the connected system after any slight disturbance. The solutions of this system

Figure 13. Diagram of interconnected regulating system

a—Exciter armature
b—Regulator armature
c—Exciter field
d—Alternator armature
f—Alternator field
g—Rheostat operating arm
h—Regulator rheostat
m—Regulator coil
p—Stabilizer primary
r—Rectifier
s—Stabilizer secondary



$$
\begin{array}{c|ccccccccccc|}
 & m & b & h & g & c & a & f & r & d & p & s \\
\hline
m & r_m+L_m p & \frac{\partial\psi_m}{\partial\theta^b}p & & & & & & & & & \\
b & \frac{\partial T_e}{\partial i^m} & \frac{\partial T_e}{\partial\theta^b}-\frac{\partial T_\Sigma}{\partial\theta^b}-m_b p^2 & & & & & & & & & \\
h & & & r_h+\frac{\partial r_h}{\partial i^h}i^h & \frac{\partial r_h}{\partial\theta^g}i^h & & & & & & & \\
g & & & 0 & -m_g p^2 & & & & & & & \\
c & & & & & r_c+L_c p & 0 & & & & & \\
z=a & & & & & -\frac{\partial E_c}{\partial i^c} & r_a+L_a p & & & & & \\
f & & & & & & & r_f+L_f p & 0 & M_{fd}p & & \\
r & & & & & & & -\mu_r\frac{\partial E_f}{\partial i^f} & r_r & -\mu_r\frac{\partial E_f}{\partial i^d} & & \\
d & & & & & & & -\frac{\partial E_f}{\partial i^f} & 0 & -\frac{\partial E_f}{\partial i^d} & & \\
p & & & & & & & & & & r_p+L_p p & \frac{1}{n}M_{sp}p \\
s & & & & & & & & & & \frac{1}{n}M_{sp}p & \frac{1}{n^2}r_s+\frac{1}{n^2}L_s p \\
\hline
\end{array}
\qquad (2)
$$

of equations express the values of these departures as functions of time. These functions of time consist of the real parts of a series of terms of the form

$$A\epsilon^{\alpha t} \qquad (10)$$

where A is an arbitrary constant and α is in general a complex number. α is always a root of the algebraic equation in powers of p formed by setting equal to zero the determinant of the system of equations defined by equation 5. This determinant is

$$D=a_6p^6+a_5p^5+a_4p^4+a_3p^3+a_2p^2+a_1p+a_0 \qquad (11)$$

where the a's are determined by the constants of the system.

If the real part of the complex number, α, is positive, the term, $A\epsilon^{\alpha t}$, increases with increasing time. This means that after a slight disturbance the currents do not tend to return to their steady-state values, but increase until the departures, Δi, are so large that they become limited by saturation or some other change in the system constants. Hence, the system is defined as being unstable if the real part of any root, α, of the determinant (11) is positive.

The existence of a root having a positive real part may be detected by the use of Routh's criterion without actual solution for the roots of the determinant (11). Routh's criterion depends upon the relative values of the a's of (11) and, in general, requires the substitution of numerical values for the system constants which determine the values of the a's. The effect of varying system constants may be found by trial.

Use of Simplifying Assumptions

It has been found possible to simplify the analysis of stability by making certain assumptions which appear reasonable.

(*a*). The alternator load current, i^d, may be assumed to be zero, since experience has shown that in general the system is more stable when the generator is loaded than at no load.

(*b*). Calculations on stability of typical systems have indicated that it is justifiable

$$
\begin{array}{c|cccccc|}
 & c' & f' & p' & m' & b' & d' \\
\hline
c' & r_h+\frac{\partial r_h}{\partial i^h}i^h+r_c+r_a-\frac{\partial E_c}{\partial i^c}+(L_a+L_c)p & r_a+L_a p & r_a+L_a p & 0 & \frac{\partial r_h}{\partial\theta^g}i^c & 0 \\
f' & r_a+L_a p-\frac{\partial E_c}{\partial i^c} & r_a+r_f+(L_a+L_f)p & r_a+L_a p & 0 & 0 & M_{fd}p \\
z'=p' & r_a+L_a p-\frac{\partial E_c}{\partial i^c} & r_a+L_a p & r_a+r_p+(L_a+L_p)p & -\frac{1}{n}M_{sp}p & 0 & 0 \\
m' & 0 & -\mu_r\frac{\partial E_f}{\partial i^f} & -\frac{1}{n}M_{sp}p & r_m+r_r+\frac{1}{n^2}r_s+\left(L_m+\frac{1}{n^2}L_s\right)p & \frac{\partial\psi_m}{\partial\theta^b}p & -\mu_r\frac{\partial E_f}{\partial i^d} \\
b' & 0 & 0 & 0 & \frac{\partial T_e}{\partial i^m} & \frac{\partial T_e}{\partial\theta^b}-\frac{\partial T_\Sigma}{\partial\theta^b}-(m_b+m_g)p^2 & 0 \\
d' & 0 & -\frac{\partial E_f}{\partial i^f} & 0 & 0 & 0 & -\frac{\partial E_f}{\partial i^d} \\
\hline
\end{array}
\qquad (5)
$$

to neglect stabilizer magnetizing current. The effect of this assumption may be represented by the equation

$$\boldsymbol{z}'' = \boldsymbol{C}_t' \cdot \boldsymbol{z}' \cdot \boldsymbol{C}' \qquad (12)$$

where

$$\begin{array}{rc} & \begin{array}{cccc} \boldsymbol{c}'' & \boldsymbol{f}'' & \boldsymbol{m}'' & \boldsymbol{b}'' \end{array} \\ \begin{array}{r} \boldsymbol{c}' \\ \boldsymbol{f}' \\ \boldsymbol{C}' = \boldsymbol{p}' \\ \boldsymbol{m}' \\ \boldsymbol{b}' \end{array} & \left|\begin{array}{cccc} 1 & & & \\ & 1 & & \\ & & 1/n & \\ & & 1 & \\ & & & 1 \end{array}\right| \end{array} \qquad (13)$$

(*c*). Calculations for typical systems have indicated that it is justifiable to make the further simplifying assumptions that exciter armature resistance, r_a, and exciter armature inductance, L_a, are zero.

On the basis of the assumptions of (*a*), (*b*), and (*c*), equation 5 becomes

$$\begin{array}{rc} & \begin{array}{cccc} \boldsymbol{c}'' & \boldsymbol{f}'' & \boldsymbol{m}'' & \boldsymbol{b}'' \end{array} \\ \begin{array}{r} \boldsymbol{c}'' \\ \boldsymbol{f}'' \\ \boldsymbol{z}'' = \quad \boldsymbol{m}'' \\ \boldsymbol{b}'' \end{array} & \left|\begin{array}{cccc} R_D + L_c p & 0 & 0 & \dfrac{\partial r_h}{\partial \theta^g} i^c \\ -\dfrac{\partial E_c}{\partial i^c} & r_f + L_f p & 0 & 0 \\ -\dfrac{1}{n}\dfrac{\partial E_c}{\partial i^c} & -\mu_r \dfrac{\partial E_f}{\partial i^f} & r_T + L_T p & \dfrac{\partial \psi_m}{\partial \theta^b} p \\ 0 & 0 & \dfrac{\partial T_e}{\partial i^m} & -X_D - mp^2 \end{array}\right| \end{array} \qquad (14)$$

where

$$r_T = \frac{r_p + r_s}{n^2} + r_m + r_r$$

$$L_T = \frac{\partial \psi_m}{\partial i^m} + \frac{1}{n^2}(L_a + L_s + L_p - 2M_{sp})$$

The determinant of equation 14 is

$$\text{Det.} = b_5 p^5 + b_4 p^4 + b_3 p^3 + b_2 p^2 + b_1 p + b_0 \qquad (15)$$

where the *b*'s are functions of the resistances, inductances, and other physical constants of the system.

If the physical constants of a system are known, stability may be studied by applying Routh's criterion to the *b*'s of (15) in the same manner in which it was applied to the *a*'s of (11). For the special case, *m* is zero, $b_5 = 0$, and $b_4 = 0$.

From calculations of this sort the stability characteristics shown in figures 8, 9, 10, and 11 were determined.

Summary

The major factors involved in the design and application of the direct-acting regulator and their relation to each other have been discussed. An outline has been presented of the mathematical method by which these relations were derived. Finally it has been shown that the modern direct-acting regulator, when properly designed for the system in which it must function, satisfies all the fundamental requirements of a regulating system.

References

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3. Tensor Analysis of Networks (a book), Gabriel Kron. John Wiley and Sons, Inc., New York, 1939.

The Application of Tensors to the Analysis of Rotating Electrical Machinery, Parts I–XVI (a book), Gabriel Kron. *General Electric Review*, 1938.

Discussion

F. E. Crever (General Electric Company, Schenectady, N. Y.): The system analyzed in this paper is by far the most usual in which the direct-acting regulator is employed and hence the very thorough analysis made is of particular interest. The use of the direct-acting regulator is of course not limited to such a system. A great many of the direct-acting-regulator applications have been made to regulate not only voltage but current, speed, torque, tension, and other quantities both in the central-station field and in industrial plants. The outstanding problem in such applications is to obtain stability and good regulation together. As the paper points out, a great many of the factors that favorably influence regulation have a tendency to decrease the stability. In general the method of analysis employed by the authors can be applied to any regulating system. The tensor method is particularly applicable in that it allows the equations of the component parts of the system to be set up and then to be readily combined to represent a complex system. The characteristic denominator of the system of differential equations is usually of a high degree so that simplifying assumptions are necessary to obtain a ready solution. The authors have been very careful in the assumptions made, which accounts for the good agreement between the analysis and practical results.

C. Concordia (General Electric Company, Schenectady, N. Y.): There are two points in this paper which I should like to amplify.

First we note that it is stated that the exciter-field inductance should be increased to improve stability. Since some investigators have concluded that all time lags in the amplification stages should be as small as possible for stability, it is of interest to comment on this conclusion. Study of the performance equations shows that the reason a certain amount of lag may be desirable is the presence of mutual terms (that is, mutual reactions between various stages) in addition to the components of the amplification factor, or the presence of second order lags (for example, the regulator-armature inertia). The mutual reactions may arise either from the stabilizer or from inherent mutual effects.

These considerations bring out the importance of studying the actual system equations, as was done in this paper, rather than an idealized system in which some of the mutual effects may be left out.

A second point to be commented on is the effect of friction in the regulator armature. It is evident that friction must be small if the regulator stability factor X_D is to be made very small. Moreover, calculations show that such friction (treated as viscous damping) is detrimental to stability and thus indicate an additional advantage of minimizing the regulator friction. Figure 4 shows one well-known mounting for accomplishing this result. Regulator friction was introduced into a system having nearly the constants of figure 9 of the paper, with results as follows:

D	M	R_D	X_D
0	0	0	0.003
0.0022	0	0	0.026
0	0.0000737	0	0.028
0.0022	0.0000737	0	0.031

where

D is the damping coefficient and $D = 0.0022$ is about one-half the value required for critical damping with $X_D = 0.09$.

M is the regulator-armature inertia.

R_D is the exciter stability factor, taken as zero in this case.

X_D is the minimum value of regulator stability factor required for stable operation.

C. E. Valentine (Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): The authors have developed an interesting analysis of a regulating system. Except for the mathematical treatment by means of the tensor method, which appears more complicated than simple to many engineers, the assumptions made and conclusions reached are, in general, quite in line with operating experience.

Of particular interest is one of the general conclusions (2*b*) that in order to improve stability, the moment of inertia of all the movable parts of the regulator should be reduced. This has been recognized for some time as a fundamental feature of a direct or indirect-acting type of regulator. In the "Silverstat" regulator described in AIEE Paper 39-91 (AIEE Transactions, volume 58, 1939, pages 838–44) a lightweight quick-acting moving arm was used even in the earliest design.

This same feature has been used consistently on all later designs which have also achieved an enviable record of performance both on single generators and generators in parallel.

The adoption of the crossed-leaf type spring mounting (also described in the earlier paper) for the moving element and the extension of this idea in the form of a spring for actuating the variable-resistance member, as shown schematically in figure 4, is a desirable improvement over the bearings and linkage previously used. The crossed-

spring type of hinge has a background of most satisfactory performance as the supporting means for the moving arm on the Silverstat generator voltage regulators where it has been used from the start.

K. A. Oplinger (Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): The authors have pointed out the possibility of using a nonlinear resistance characteristic in a regulator as a means of improving regulation. It would appear difficult to make this nonlinear characteristic such that the slope of the exciter-field-circuit resistance line always approaches the slope of the exciter saturation curve. I would like to ask if it has been practical to do this for all types of exciters, and if so, what actual improvement in regulation is secured taking into account that R_D will change appreciably with exciter saturation and field temperature?

The general conclusions of the authors under (2*c*) state that the exciter field inductance should be increased in order to improve stability. Since this conclusion is not in agreement with experimental results, could not this conclusion be in error due to assumptions made regarding the size of the stabilizer?

C. R. Hanna (Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): The accuracy of a voltage regulator is determined by the over-all amplification factor of the system which is the ratio of the change in generated voltage to the deviation in terminal voltage. The authors give the equation for the amplification of their regulator at the bottom of figure 7 of their paper. It would have been more instructive if data on system stability had been given in terms of the amplification instead of just the X_D and R_D factors which as indicated in their equation, only partially determine the amplification.

The curves given show only the limiting conditions for stable operation. No computations are made of damping conditions corresponding to points in the stable range. It is necessary to have large decrements of any system oscillations so that disturbances due to load changes, etc., will not cause continuous swinging of the voltage. Points in the stable range may not be selected indiscriminately because the damping may still be too low for practical operation.

In the interests of simplifying a problem as involved as that of voltage regulation, many variables have to be eliminated or assumed to have a small influence. The authors make one assumption, however, which is difficult to justify; namely, that the stabilizer magnetizing current is zero. This means infinite self- and mutual inductance and, therefore, a transformer of infinite size. Such an assumption completely ignores the problem of determining just how large the stabilizer should be for a good practical result.

The mathematical processes used in the paper could have been employed to yield much more design information than is given. One is somewhat disappointed that the numerical results do not include such pertinent information as rates of decay of oscillations or methods of predicting transformer size for a given system. As shown in the recent paper by the writer and his collaborators on "Recent Developments in Voltage Regulation" (AIEE Transactions, volume 58, 1939, pages 838–44) these can be computed by less involved processes than the method of tensors as used by the authors.

W. K. Boice, S. B. Crary, Gabriel Kron, and **L. W. Thompson:** Mr. Hanna suggests that simpler methods could be used which would yield more easily the damping factors. The equations in the paper can be simplified to almost any extent by making assumptions or neglecting the effect of certain factors so that they will yield the damping factors directly, or with little numerical work. This is usually accomplished at a sacrifice of accuracy and, what is more important, at a sacrifice of the ability to determine the effect of factors which influence the regulator and excitation-system design. In many cases, it is advisable to make simplifying assumptions only after a more general approach has been made. In this way the simplifying assumptions may be tested for validity.

Mr. Hanna questions the validity of neglecting stabilizer magnetizing current. The calculations which we have made for a typical system have indicated that this could be done with small error. However, the influence of stabilizer magnetizing current was studied and can be further studied by using the corresponding more general equations presented in the paper.

Mr. Oplinger questions the value of the nonlinear stack-resistance characteristic in that it would be difficult in practice to have the exciter characteristic slope always correspond to the field circuit resistance line. It is not necessary and is practically impossible that these characteristics correspond for all loads. However, the nonlinear stack resistance for any given load condition results in better regulation than a linear-characteristic regulator-stack resistance. It is in the direction to improve the regulation and is accordingly desirable from this standpoint.

For the typical system which we have studied, the analysis showed that an increase in field inductance improved stability. This would not necessarily be true for any system, particularly one whose constants or connections deviated materially from those chosen for study. However, experience with direct-acting regulators over a period of years has indicated for a wide range of typical systems that increased exciter field inductance is in the direction to improve stability.

Mr. Concordia's comments and contributions on regulator friction are appreciated and can be considered a valuable addition to the material presented in the paper.

We are pleased to learn from Mr. Valentine that he has also found the crossed-spring type of hinge and low moment of inertia to be most satisfactory. This type of design has definite advantages.

We wish to thank Mr. Crever for emphasizing that the method presented in the paper may be used for other types of regulating systems.

Signal System, Interlocking Plants, and Automatic Train Control on the San Francisco-Oakland Bay Bridge Railway

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Synopsis: This paper briefly describes the nature and purpose of the various groups of railway signal and interlocking equipment operated in connection with railway service over the San Francisco-Oakland Bay Bridge. Following this description is an explanation of the method used in determining the lengths of signal blocks and calculating safe braking distances throughout the project. It is hoped that the presentation of this paper will lead to further discussion and research concerning the braking of trains of this type.

THIS eight-mile-long double-track railway with its "train-a-minute" operation called for the most complete and modern system of block signalling and train control, and required the maxmium facility for operating the switches and wayside signals at the San Francisco terminal, at the Oakland yard, and at the junction of the two railways. The means by which these extreme requirements were met, the choice throughout of electrical equipment in preference to nonelectrical mechanical devices, the design of an electromechanical "brain" consisting of 3,000 relays with their interlocking circuits, the certain and safe solution of new and unique circuit problems, comprise the history of the installation. Signal blocks are here, but no signals are visible along the tracks. Instead, there is a four-speed signal in the cab directly before the eyes of the motorman. Should the train exceed the speed indicated, an automatic brake application brings the train to a stop. The method used for the calculation of safe braking distances and the determination of suitable block lengths may interest those who are confronted with similar problems.

An interlocking control machine at which the operator merely pushes two buttons on a track diagram to set up a route, position the switches, and clear the signals, automatically and infallibly avoids the authorizing of any conflicting or unsafe move. If, for any reason, the customary or preferred route between the two points is not available, the machine will unerringly select and set up another route, if any be available, between the two points. On these same control boards are the operating buttons and indication lights of a system for the transmission, reception, and storage of the identities of trains of the 15 lines of the Oakland and Berkeley network. In each tower, one in San Francisco and one in Oakland, the operator has at all times a visible picture of the trains approaching on the bridge, and the identity of the nearest three is always shown.

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Cab-Signal and Train Control System

The system is a true automatic block system with double-rail track circuits, using reactance or impedance bonds at the insulated joints to provide a path for the negative return of the power current, but having no visible block signals whatsoever. Instead of semaphore arms automatically taking various angles, the 100-cycle signal current in the rails is uniformly interrupted, the rate of interruption in each block depending on its distance behind the occupied block. A clear track ahead is denoted by 180 interruptions per minute, occupancy less than "clear track" distance by 120 interruptions per minute, occupancy in the second block ahead by 75 per minute. Occupancy in the first block ahead or in the immediate block is denoted by a steady current or by no current. Receivers at the front end of the train pick up the signal current by induction, filtering and amplifying it, and the interruption rate picks up the corresponding rate relay on the train, thereby selecting the cab-signal light and the set of governor contacts which will remain in control so long as that code continues to be picked up.

Whenever the train reaches the authorized speed as indicated by the cab signal, a white light is lighted, and remains lighted as long as the speed equals or exceeds that indicated. Should the speed be increased until it is one mile per hour greater than that authorized, a warning signal sounds and continues sounding until the speed is reduced below that point. Should the train continue to accelerate and reach a speed two miles in excess of that authorized, an immediate emergency brake application will automatically result and the train is brought to a full stop. When the cab-signal aspect changes to indicate a lower speed, and the train is not already down to this new authorized speed, the motorman is allowed $2^1/_2$ seconds in which to initiate a service-brake application which he must hold until the train is down to the authorized speed. Any delay beyond that period will cause an automatic emergency application of the brakes and the train will be brought to a full stop. When the aspect changes to the lowest-speed indication, the motorman, in addition, must step on an "acknowledging contact" pedal for, though he may be traveling below that speed and consequently not be required to apply the brakes, he must indicate that he is alert and prepared to stop in case the block ahead is occupied.

The designed arrangement of codes and controls is given in table I.

An additional code of 240 interruptions per minute, used at points where trains leave cab-signaled tracks, cancels the cab-signal and train-control equipment on the train, lights a violet light in the cab signal showing the letters "NS", and permits the train to proceed without speed restrictions until a control code is again encountered.

In such an automatic block system the controls are set up by the occupancy or nonoccupancy of a track block. The 100-cycle current is supplied to the track circuit through a low-voltage transformer whose leads are connected to the two rails at the exit end of the block. At the entrance end the track relay leads are connected in a similar manner and current-limiting resistances connected in series at either or both ends. When the signal current is shunted through a train axle in the block, the track relay drops and thereby initiates the resulting changes in the controlling circuits.

Signal Power Supply

The 100-cycle a-c energy for the signal system is supplied by duplicate motor

generator sets in the mole substation. One set provides ample power for the entire bridge railway, the other serving as a standby. The two sets are controlled by equipment which functions automatically to start and cut into service the standby in the event of any failure of the operating set.

Distribution of the 100-cycle energy is made at 2,300 volts with line transformers at frequent intervals stepping down the potential to 110 volts for service to the track transformers and code transmitters and to the rectifier transformers supplying the control circuits and their d-c relays.

The two-conductor 2,300-volt distribution cable is in duplicate, or looped, from end to end of the project. Oil switches on either side of each line transformer enable a transformer, or a section of cable between transformers, to be cut out without de-energizing other portions of the installation.

Interlocking Plants

In the Oakland yard, the interlocking plant includes the main tracks, the eight set-out tracks, the connections and switches between such tracks, switches for entering or leaving these tracks, and all signals governing routes through these interlocked switches. There are 36 interlocked switches and 62 color-light signals of the searchlight type in this plant. Main-track signals for the normal direction of traffic are one-unit or two-unit high signals. All others are single-unit dwarf signals. At the eastbound divergence from joint track, the signal carries two white marker lights to indicate to the approaching train whether the switch is set for the Key System or the Interurban Electric connection. To give the approaching train the earliest possible warning, or assurance, as the case may be, the marker light is repeated at two preceding high signals.

In the San Francisco terminal loop, all switches and signals are interlocked. There are 36 switches and 40 dwarf signals.

Cab-signal blocks with code in the normal direction of traffic are carried continuously through both interlocking plants. The wayside signals are therefore primarily route signals but are arranged to operate in a manner consistent with track conditions. A yellow clear indicates a "no code" condition in the immediate block; that is, the motorman must expect that upon passing a yellow wayside signal, a "Red 11" cab signal will be received. With the normal control, a cleared signal will return to stop when the head of the train passes it; that is, the signal is a "stick" signal responsive to the occupancy of the immediate block. With a special control, however, the signal is made "non stick", will not be returned to stop by a passing train, and may be cleared even when the immediate block is occupied. Signals at entrances to cab-signal territory such as those leading from storage tracks to set-out tracks in the Oakland yard are known as "TC" signals. When a "TC" signal is cleared with the immediate block occupied, the aspect is a flashing yellow instead of steady yellow. With this aspect showing, the train comes to a stop before passing the signal. The choice of clear aspect, whether green, steady yellow, or flashing yellow, is automatic and entirely dependent on track conditions and not at all dependent on the choice between normal and special control.

Interlocking circuits are so arranged that a signal may not be cleared unless all switches in the route governed are properly positioned. Opposing or conflicting signals may not be clear at the same time. A switch may not be thrown while its block is occupied. No switch may be moved unless all signals governing through that switch are at stop. If a signal is thrown to stop in the face of an approaching train, switches in the route

Table I

Code Interruptions Per Minute	Cab Signal Aspect	Nominal Authorized Speed (MPH)	Speed Above Which White Light Is Lighted (MPH)	Speed Above Which Warning Signal Is Sounding (MPH)	Speed at Which Emergency Brakes Are Automatically Applied (MPH)
180	Green 35	35	35	36	37
120	Yellow and green 25	25	25	26	27
75	Yellow 17	17	$16\frac{1}{2}$	$17\frac{1}{2}$	$18\frac{1}{2}$
None	Red 11	11	$10\frac{3}{4}$	$11\frac{3}{4}$	$12\frac{3}{4}$

Figure 1. Typical time-distance chart

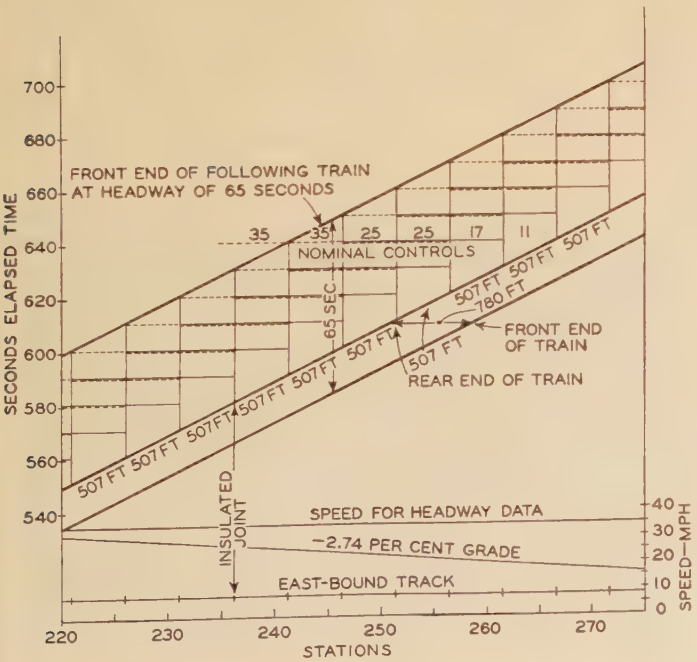
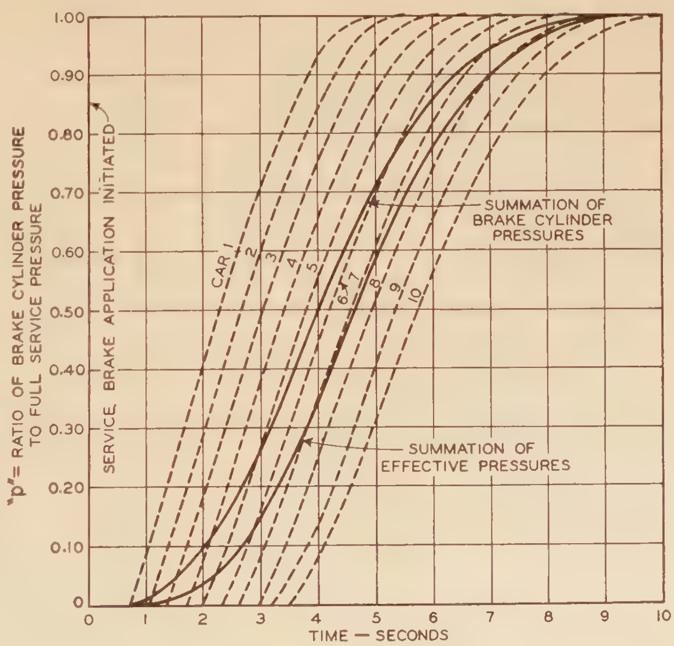


Figure 2. Initial rise in brake pressures



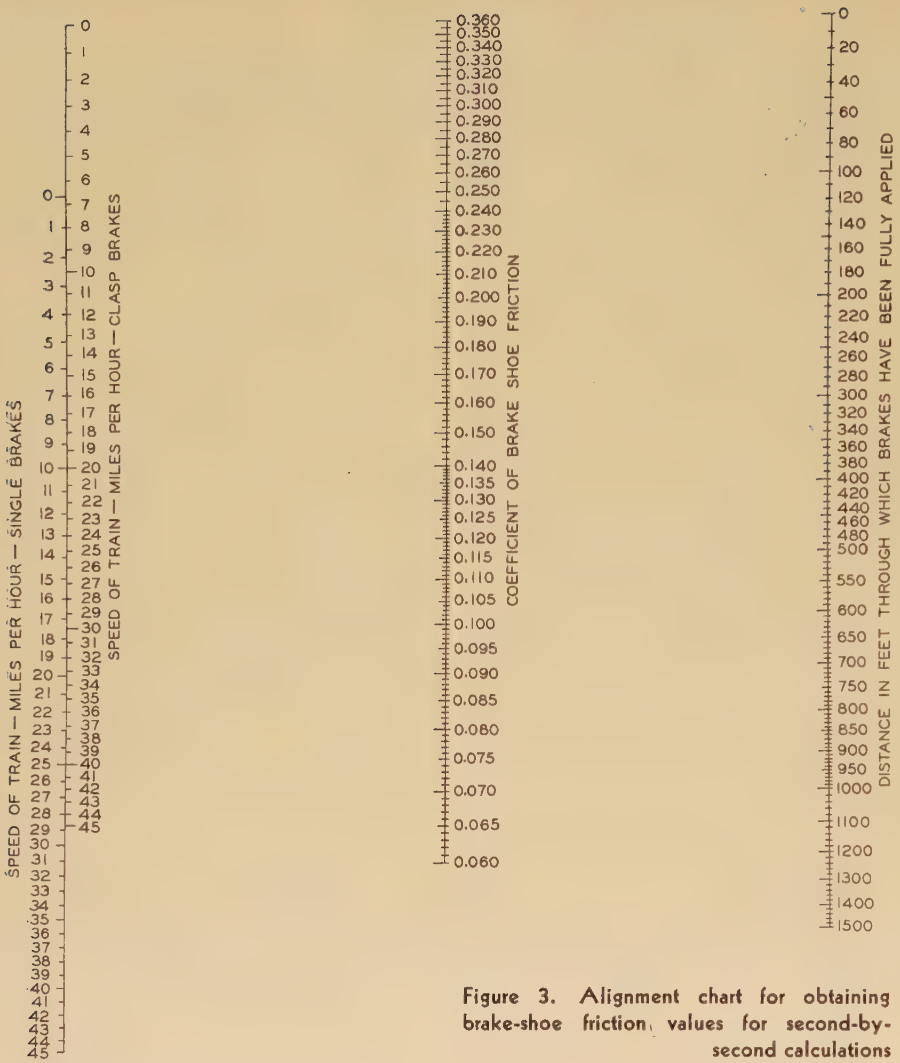


Figure 3. Alignment chart for obtaining brake-shoe friction values for second-by-second calculations

will remain locked until a safe time interval has elapsed.

NX Control Machines

The control machines at the two interlocking plants are the latest development in equipment for this purpose and are designed to provide the utmost facility for speed and precision of interlocking control. The various controls and indications are arranged directly on a track diagram so that memorizing of lever numbers and their related functions is not required.

To "set up a route" in the interlocking plant, that is, properly to position the switch or switches and clear the signal, it is necessary only to push the initiation button at the entrance to the route and then push the completion button at the exit from the route. As soon as the switches have operated to their proper positions, the signal will clear. The train passes through, restoring the signal to stop and releasing each switch as it passes out of its block.

A series of adjoining routes may be operated as one, this being known as end-to-end operation. It is necessary only to press the initiation button of the first route and the exit button of the last route and all intervening switches will properly position and intermediate signals will clear as well as the initial signal. In many instances of end-to-end operation, more than one route exists between the two points. The preferred route will be automatically selected and set up if it is available. If for any reason it is not available, the machine will automatically select and set up the optional route. One end-to-end location in San Francisco has four possible routes which are automatically selected as available in their prescribed order of preference.

When initiating a route, the initiating button may be operated in either of two ways. It may be pushed or it may be rotated 90 degrees. If the route is set up by pushing the initiating button, any occupancy of the block immediately beyond the signal will return the signal to stop; therefore, the route may not be set up by this means if this immediate block is occupied. If the route is set up by rotating the initiating button, occupancy of the immediate block will not return the signal to stop and the route will remain set up for any following train or trains. A route that is set up may be cancelled by pulling the initiating button, if it had been pushed, or by rotating it back to the normal position, if it had been rotated.

On the San Francisco control board, in addition to the indications of signals, switches, and occupancy, a green light is provided on each of the six lines representing the six tracks in the train shed. When a train is ready to leave, the conductor presses a button on the platform. The corresponding green light on the board is lighted and remains lighted until the dwarf signal is cleared, authorizing the train to leave the shed.

The *NX* control machine contains the least possible quantity of the necessary control equipment; the push button and miniature switch contacts, the various indicators, and the thousand-odd terminal screws. The relays with their interconnections, the equipment which constitutes the automatic "brain" of the machine, is in a separate room. Approximately 1,000 wires connect the control board with the relay room. The relays are of the plug-in quick-detachable type, mounted on panels two feet wide by

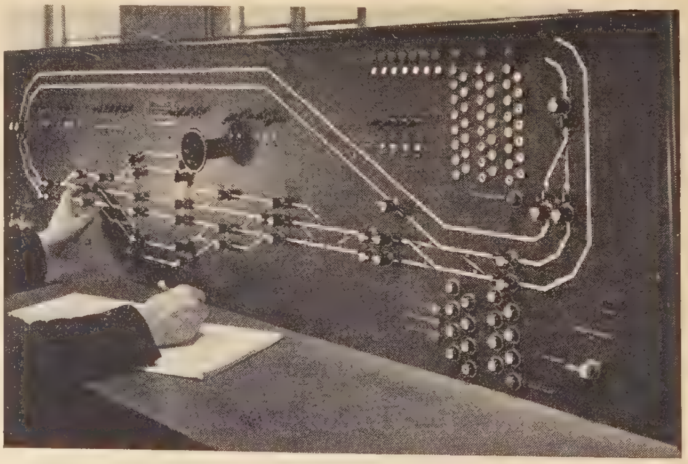
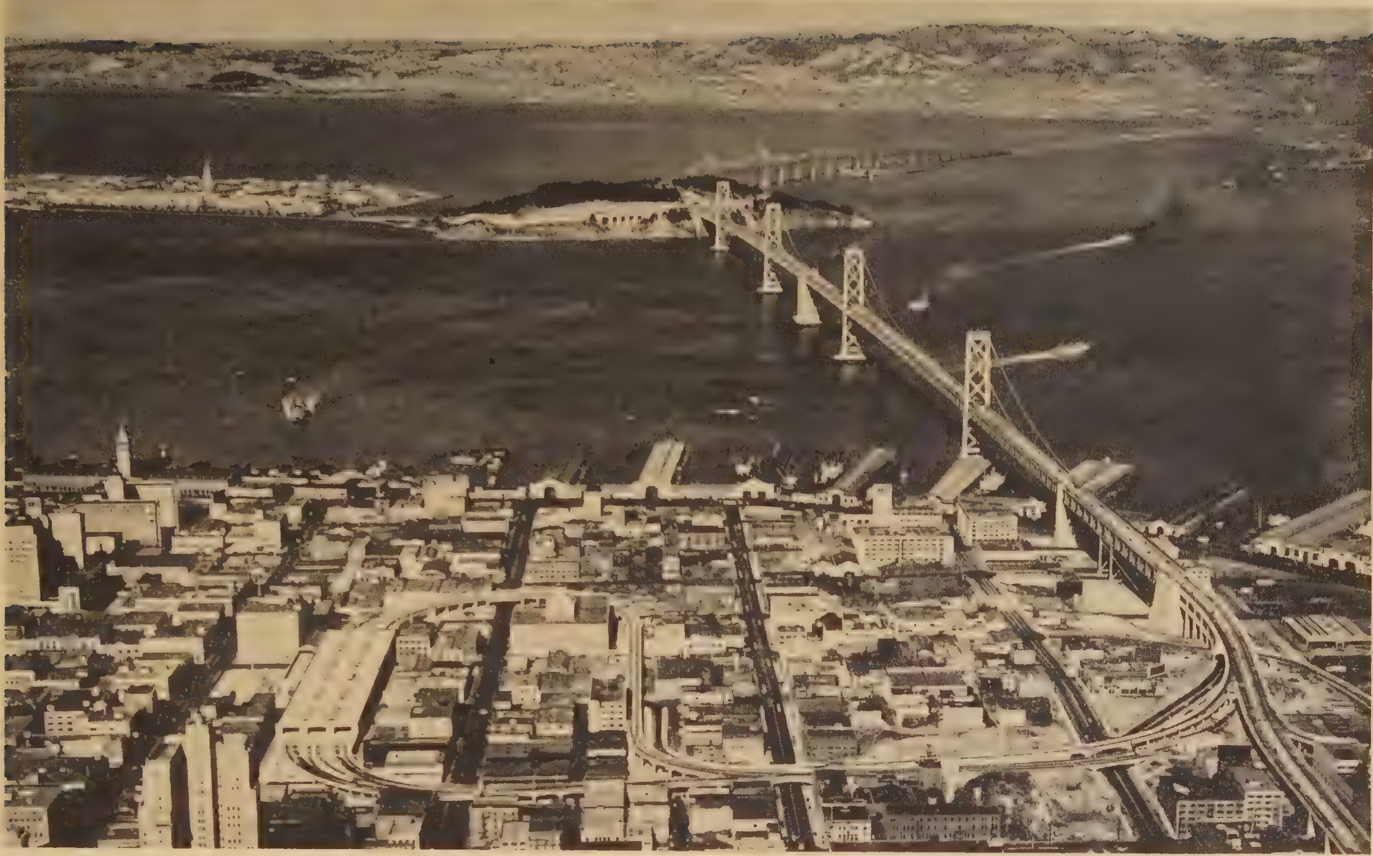


Figure 4. San Francisco control board



eight feet high. In San Francisco 22 of these panels, mounted back to back with a passageway between, contain 865 such relays. In Oakland the interlocking plant is naturally divided into eight groups of interlocked switches and signals. At each group remote from the tower is a "bungalow" containing the relays and the protective interlocking of circuits for that particular group. Only the necessary remote control and indication wires are carried from the bungalow to the control room. There are six such bungalows in the Oakland yard, the tower serving the purpose directly for two of the groups, and the number of relays is 1,328. In housings along the bridge between the two interlocking plants are 500 additional relays.

Figure 5. Air view showing the tracks of the San Francisco terminal loop

Train Describer Equipment

On each control machine at the right-hand end of the board is a special group of buttons and a group of lights which constitute the visible controls of the train describer equipment. These buttons and lights are lettered and numbered in accordance with the established identities of the various trains. When a train is given its outgoing route from the San Francisco plant, the operation is, as usual, the pushing of the entrance and the exit buttons. But in this case, instead of operating the regular exit button, the control-board operator is required to press one of this special group, thus setting up the identity of the outgoing train, as well as setting up and clearing the route. When the train accepts the signal the identity is transmitted to the Oakland control machine where it is eventually displayed in the group of lights on that board.

This system so functions that the nearest train approaching the plant is identified by the proper light in the number 1 group of 15 lights, the next train by a light in the second group and the third train by a light in the third group. The presence of additional approaching trains is shown by a single light for each. When a train passes the first signal of the interlocking plant, its identity light in number 1 bank is cancelled. The train identity shown in bank number 2 then jumps into number 1, that shown in number 3 moves into number 2, and the indication of the train shown by the single light of number 4 passes into bank number 3 and becomes identified. By this means the operator at the control machine may always see the identity of the next three trains to enter the plant and can plan accordingly.

The train identities to the number of 15 are transmitted in either direction over a single pair of wires by means of variations in the polarities of four successive d-c impulses. The equipment includes 170 train describer relays at San Francisco and 102 at the Oakland control station.

Automatic Sorting of Trains

Although designed primarily for informing the tower of the identities of approaching trains, an additional and unique use is made of the train-describer system in controlling the entrance switch to the San Francisco interlocking. The identities of Interurban Electric trains are shown by numbers and those of the Key System by letters. Tracks 1, 2, and 3 in the terminal are assigned to the Interurban Electric Railway, and tracks 4, 5, and 6 to the Key System. At the entrance switch the preferred route for the Interurban Electric is therefore over the right-hand track and for the Key System over the left hand. In place of pushing the buttons to set up the proper route for each approaching train, the operator switches on "automatic sorting". The identification of each train is held by a bank of four relays. Number 1 of this bank is down for the numbered descriptions and up for the lettered descriptions. A front or a back contact of this number

1 relay is used to select the route and completion is automatic as soon as the switch is released by the passing train. The operator is thus enabled to forget the entrance switch entirely and all Interurban Electric trains are automatically routed over the right-hand track and all Key System trains over the left.

Train Describer Repeaters

The San Francisco control machine includes, in addition to the regular train-describer equipment, two groups of indication lights known as train-describer repeaters. These are mounted at the left end of the board and carry the descriptions after they are automatically cancelled at the entering switch until the trains pass the point from whence they are normally routed, each to its individual track in the station. Either of the two incoming tracks may be occupied by five short trains at one time and each repeater therefore is equipped with five groups of description lights. As the train passes through the entering switch its description is cancelled from the main describer, and enters the *N* repeater or the *R* repeater in accordance as the switch was in the normal or the reverse position.

Determination of Block Lengths

The extremely close headway between trains on the Bridge Railway, together with the heavy grades and frequent changes in grade, necessitated an unusually careful and elaborate investigation to determine the correct layout of signal blocks throughout the length of the project. It is necessary that these blocks and their controls not only permit the desired headway, but also provide safe braking distances at all points and under all conditions. The investigation included tests of the equipment actually operated over the bridge, as well as studies of existing data.

To verify the headway the signal blocks were laid out in the usual manner on time-distance charts. Figure 1 shows a typical portion of one of these charts where the grade is descending 2.74 per cent and the speed is constant at 35 miles per hour. The line designated as "front end of train" is first calculated and drawn. Where the speed is not constant a step-by-step method is used for the calculation. Scaling the train length of 780 feet to the left of this line, a second line is drawn parallel, representing the rear end of the same train at any instant. Still parallel to the first line, but scaling 65 seconds above it, a third line is drawn representing the front end of the following train.

A horizontal line drawn across these three lines will correctly represent the relative positions of the two trains at a given instant in time and, if the blocks are projected vertically from the track plan to this horizontal line, the arrangement of signal blocks between the two trains is shown. By drawing the hori-

Table II. Interurban Electric Railway Ten-Car Train, Test Condition, Braking From 30 Miles Per Hour, Level Grade

t	V	p	f	$R_b = 16.4pf$	$R_t = \frac{V+45}{450}$	$R = R_b + R_t$	V_a	D	SD	d	Sd	Sd_a
0	30.00											
1	29.83	0		0	0.17	0.17	29.92	43.9	43.9	0		
2	29.64	0.01	0.150	0.02	0.17	0.19	29.74	43.6	87.5	0.4	0.4	0.2
3	29.27	0.08	0.150	0.20	0.17	0.37	29.46	43.2	130.7	3.5	3.9	2.1
4	28.52	0.24	0.150	0.59	0.16	0.75	28.90	42.4	173.1	10.2	14.1	9.0
5	27.24	0.46	0.149	1.12	0.16	1.28	27.88	40.9	214.0	18.8	32.9	23.5
6	25.44	0.68	0.147	1.64	0.16	1.80	26.34	38.6	252.6	26.2	59.1	46.0
7	23.26	0.85	0.146	2.03	0.15	2.18	24.35	35.7	288.3	30.3	89.4	74.2
8	20.86	0.94	0.146	2.25	0.15	2.40	22.06	32.4	320.7	30.4	119.8	104.6
9	18.36	0.98	0.147	2.36	0.14	2.50	19.61	28.8	349.5	28.2	148.0	133.9
10	15.80	1.00	0.149	2.42	0.14	2.56	17.08	25.0	374.5	25.0	173.0	160.5
11	13.16		0.153	2.51	0.13	2.64	14.48	21.2	395.7	21.2	194.2	183.6
12	10.41		0.160	2.62	0.13	2.75	11.79	17.3	413.0	17.3	211.5	202.8
13	7.52		0.169	2.77	0.12	2.89	8.97	13.2	426.2	13.2	224.7	218.1
14	4.46		0.180	2.95	0.11	3.06	5.99	8.8	435.0	8.8	233.5	229.1
15	1.12		0.197	3.23	0.11	3.34	2.79	4.1	439.1	4.1	237.6	235.5
15.3	0		0.210	3.42	0.10	3.52	0.56	0.3	439.4	0.3	237.9	

NOTE: Two tests made under the above conditions resulted in measured distances of 429 feet and 431 feet, respectively.

Table III. Interurban Electric Railway Ten-Car Train, Braking From 37.74 Miles Per Hour, Minus Three Per Cent Grade

t	V	p	f	$R_b = 16pf$	$R_t = \frac{V+45}{450}$	$R = R_b + R_t - 0.61$	V_a	D	SD	d	Sd	Sd_a
0	37.74											
1	38.17	0		0	0.18	−0.43	37.95	55.6	55.6	0		
2	38.57	0.01	0.132	0.02	0.19	−0.40	38.37	56.2	111.8	0.6	0.6	0.3
3	38.82	0.08	0.130	0.17	0.19	−0.25	38.70	56.8	168.6	4.5	5.1	2.8
4	38.75	0.24	0.128	0.49	0.19	+0.07	38.79	56.9	225.5	13.6	18.7	11.9
5	38.26	0.46	0.124	0.91	0.19	+0.49	38.50	56.5	282.0	26.0	44.7	31.7
6	37.40	0.68	0.119	1.29	0.18	0.86	37.83	55.5	337.5	37.7	82.4	63.5
7	36.29	0.85	0.113	1.54	0.18	1.11	36.85	54.0	391.5	45.9	128.3	105.3
8	35.10	0.94	0.108	1.62	0.18	1.19	35.70	52.3	443.8	49.2	177.5	152.9
9	33.91	0.98	0.103	1.62	0.18	1.19	34.50	50.6	494.4	49.5	227.0	202.2
10	32.75	1.00	0.100	1.60	0.17	1.16	33.33	48.9	543.3	48.9	275.9	251.4
11	31.64		0.097	1.55	0.17	1.11	32.20	47.2	590.5	47.2	323.1	299.5
12	30.58		0.094	1.50	0.17	1.06	31.11	45.6	636.1	45.6	368.7	345.9
13	29.55		0.092	1.47	0.17	1.03	30.07	44.1	680.2	44.1	412.8	390.7
14	28.55		0.091	1.45	0.16	1.00	29.05	42.6	722.8	42.6	455.4	434.1
15	27.56		0.090	1.44	0.16	0.99	28.06	41.2	764.0	41.2	496.6	476.0
16	26.59		0.089	1.42	0.16	0.97	27.08	39.7	803.7	39.7	536.3	516.4
17	25.63		0.088	1.41	0.16	0.96	26.11	38.3	842.0	38.3	574.6	555.4
18	24.69		0.087	1.39	0.16	0.94	25.16	36.9	878.9	36.9	611.5	593.0
19	23.76		0.087	1.39	0.15	0.93	24.23	35.5	914.4	35.5	647.0	629.2
20	22.83		0.087	1.39	0.15	0.93	23.30	34.2	948.6	34.2	681.2	664.1
21	21.90		0.087	1.39	0.15	0.93	22.37	32.8	981.4	32.8	714.0	697.6
22	20.97		0.087	1.39	0.15	0.93	21.44	31.5	1012.9	31.5	745.5	729.7
23	20.04		0.087	1.39	0.15	0.93	20.50	30.1	1043.0	30.1	775.6	760.5
24	19.10		0.088	1.41	0.14	0.94	19.57	28.7	1071.7	28.7	804.3	790.0
25	18.16		0.088	1.41	0.14	0.94	18.63	27.3	1099.0	27.3	831.6	818.0
26	17.21		0.089	1.42	0.14	0.95	17.69	25.9	1124.9	25.9	857.5	844.6
27	16.26		0.089	1.42	0.14	0.95	16.74	24.6	1149.5	24.6	882.1	869.8
28	15.30		0.090	1.44	0.13	0.96	15.78	23.1	1172.6	23.1	905.2	893.7
29	14.31		0.092	1.47	0.13	0.99	14.80	21.7	1194.3	21.7	926.9	916.0
30	13.30		0.093	1.49	0.13	1.01	13.80	20.2	1214.5	20.2	947.1	937.0
31	12.28		0.094	1.50	0.13	1.02	12.79	18.8	1233.3	18.8	965.9	956.5
32	11.22		0.096	1.54	0.13	1.06	11.75	17.2	1250.5	17.2	983.1	974.5
33	10.14		0.098	1.57	0.12	1.08	10.68	15.7	1266.2	15.7	998.8	991.0
34	9.03		0.100	1.60	0.12	1.11	9.59	14.1	1280.3	14.1	1012.9	1005.8
35	7.89		0.102	1.63	0.12	1.14	8.46	12.4	1292.7	12.4	1025.3	1019.1
36	6.70		0.105	1.68	0.12	1.19	7.30	10.7	1303.4	10.7	1036.0	1030.6
37	5.47		0.108	1.73	0.11	1.23	6.09	8.9	1312.3	8.9	1044.9	1040.4
38	4.18		0.112	1.79	0.11	1.29	4.83	7.1	1319.4	7.1	1052.0	1048.4
39	2.82		0.116	1.86	0.11	1.36	3.50	5.1	1324.5	5.1	1057.1	1054.5
40	1.39		0.121	1.94	0.10	1.43	2.10	3.1	1327.6	3.1	1060.2	1058.6
40.9	0		0.127	2.03	0.10	1.52	0.70	0.9	1328.5	0.9		1060.6

zontal lines at such points that the rear end of the train is shown as just having passed an insulated joint, the restrictive distance behind the train is at its minimum length. There must then be one full unrestricted block ahead of the following train, so that it may proceed through that block on a clear signal during the time that will elapse before the rear end of the leading train will pass beyond another insulated joint and thereby step the restrictive conditions another block forward.

In checking braking distances, the leading train is considered stationary with its rear axle immediately ahead of an insulated joint. When closing up on a standing train a restrictive block must be encountered at such a distance behind that insulated joint as will enable the motorman to bring the train from its maximum possible speed to a safe stop. This required distance includes five items as follows:

1. Travel during time required for operation of signal equipment (2 ½ seconds).

2. Travel during allowed time for motorman's reaction (2 ½ seconds).

3. Travel from initiation of service-brake application until train is stopped.

4. Safety factor for defective brakes or slippery rails, 25 per cent of item 3.

5. Overhang of two trains beyond end axles (20 feet).

Items 1 and 2 are taken together as the travel at the maximum possible speed for five seconds. The maximum possible speed under any control is the speed which would result in an automatic brake application, plus two per cent error for governor maladjustment. For the maximum fully loaded ten-car Interurban Electric train on level track the items are as follows:

Items 1 and 2, $\frac{5\times 37.74\times 5280}{3600}=$	277 feet
Item 3, level grade, from 37.74 miles per hour	1,329 feet
Item 4, 25 per cent of item 3	332 feet
Item 5	20 feet
Total	1,958 feet

It will be seen that only items 3 and 4 will vary with the grade and only item 3 requires extensive investigation.

The chief factors influencing the effect of brakes upon a railway train may be listed as follows:

1. The nominal presssure of the brake shoes against the wheels when the brake cylinders are at their full operating pressure.

2. The efficiency of the brake rigging in transmitting this pressure.

3. The coefficient of friction which enables

Table IV. Interurban Electric Railway Ten-Car Train, Braking From 18.87 Miles Per Hour, Minus Three Per Cent Grade

t	V	p	f	$R_b = 16\,pf$	$R_t = \frac{V+45}{450}$	$R = R_b + R_t - 61$	V_a	D	SD	d	Sd	Sd_a
0	18.87											
1	19.34	0		0	0.14	−0.47	19.10	28.0	28.0			
2	19.78	0.01	0.182	0.03	0.14	−0.44	19.56	28.7	56.7	0.3	0.3	0.2
3	20.02	0.08	0.180	0.23	0.14	−0.24	19.90	29.2	85.9	2.3	2.6	1.5
4	19.81	0.24	0.178	0.68	0.14	+0.21	19.92	29.2	115.1	7.0	9.6	6.1
5	18.98	0.46	0.177	1.30	0.14	+0.83	19.40	28.5	143.6	13.1	22.7	16.1
6	17.54	0.68	0.176	1.91	0.14	1.44	18.26	26.8	170.4	18.2	40.9	31.8
7	15.61	0.85	0.177	2.40	0.14	1.93	16.58	24.3	194.7	20.7	61.6	51.2
8	13.42	0.94	0.178	2.67	0.13	2.19	14.52	21.3	216.0	20.0	81.6	71.6
9	11.03	0.98	0.183	2.87	0.13	2.39	12.23	18.0	234.0	17.6	99.2	90.4
10	8.48	1.00	0.190	3.04	0.12	2.55	9.76	14.3	248.3	14.3	113.5	106.3
11	5.77		0.200	3.20	0.12	2.71	7.13	10.4	258.7	10.4	123.9	118.7
12	2.87		0.213	3.40	0.11	2.90	4.32	6.3	265.0	6.3	130.2	127.0
12.9	0		0.232	3.71	0.10	3.20	1.43	1.9	266.9	1.9		131.0

Five seconds at 18.87 miles per hour	= 138 feet
Calculated braking distance	= 267
25 per cent of braking distance	= 67
Overhang	= 20
Minimum length of one block	492 feet
Actual block on minus 3 per cent grade	507 feet

this pressure to effect a tangential force on the wheel rims.

4. The variation in effective brake pressure during the period of initial application before all brake cylinders are at their full operating pressures.

5. The weight of the train, including its load.

6. The inertia effects of rotating parts, such as wheels and axles and parts such as motor armatures which are geared to the wheels and axles.

7. The train resistance or those components of mechanical friction which oppose the motion of the train at a constant speed on tangent level track in still air.

8. The grade over which the train is moving.

9. Curvature of the track over which the train is moving.

These factors as they entered into our own particular problem were as follows:

1. Total nominal brake-shoe pressure (pounds):

Interurban Electric ten-car train, six motor cars, four trailers, with equalization at 50 pounds	942,000
With equalization at 60 pounds	1,130,400
Key System seven-unit train with single brakes	1,181,900
With clasp brakes	1,057,700

2. Brake rigging efficiency, taken in all cases as 85 per cent.

3. The most extensive records of the effect of railway brakes are of the very elaborate and lengthy series of experiments made by Captain Douglas Galton in 1878 on the Brighton Railway in England. As is true of most braking studies made since that date for speeds under 60 miles per hour, Galton's observations have been the basis for our studies and, together with the tests made with Key System and Interurban Electric equipment, comprise the data from which our friction formulas have been derived.

For use in our braking calculations the coefficient of brake-shoe friction is taken as continuously varying with the speed and with the distance through which the brakes have been applied. For clasp brakes our formula is

$$f_1 = \frac{36}{100+3V}$$

in which V is the speed in miles per hour. This gives a curve which approaches the maximum extremes observed by Galton without exceeding his maximum observation for any speed. Galton's tests were made with clasp brakes. For single brakes we have used values somewhat less than the mean of his observations, having found that such values agreed with our tests. The formula used for single brakes is

$$f_1 = \frac{9}{30+V}$$

The reduction factor for distance, F, is taken as equal to the ratio,

$$\frac{10{,}000+5d}{10{,}000+24d}$$

in which d is the distance in feet through which the brakes have been fully applied. The final coefficient is then given by the formula,

$$f = Ff_1$$

and the nomograph, figure 3, is designed for conveniently obtaining the resulting values.

The coefficient of friction at low partial pressures is assumed to vary as the square root of the pressure and this variation is included in the curve of summation of effective pressures in figure 2.

4. When a service-brake application is made, the reduction in air pressure, followed by the operation of the triple valve, is first effective in the head car and then successively in the following cars of the train. Further, the normal pressure of the brake shoes on the wheels is not applied instantly, but rises gradually from zero to full pressure. For use in making braking calculations, standing tests were made of

the rate of rise in brake cylinder pressures of an Interurban Electric ten-car train. These pressure rises were charted and, after consideration was given to the effect of reduced pressures on brake rigging efficiency and on coefficients of friction, a curve of summation of effective pressures was added to the chart (figure 2). Similar data were obtained for a Key System train of seven articulated units. The effective pressure factors for the first ten seconds of a service brake application as used in our calculations are as follows:

Second	Factor for Interurban Electric Railway	Factor for Key System
1	0.0	0.0
2	0.01	0.0
3	0.08	0.08
4	0.24	0.43
5	0.46	0.78
6	0.68	0.97
7	0.85	1.00
8	0.94	1.00
9	0.98	1.00
10	1.00	1.00

5. The weights in pounds of the various trains involved were as follows:

Interurban Electric ten-car train	970,000
Maximum passenger load	250,000
Total weight	1,220,000
Key System train with clasp brakes	952,000
Maximum passenger load	296,000
Total weight	1,248,000
Key System train with single brakes	910,000
Maximum passenger load	296,000
Total weight	1,206,000

6. We have found that the inertia of the rotating parts of either of our maximum trains is equivalent to the addition of approximately 100,000 pounds to the weight. This is the weight equivalent of the rotating parts and, when this is added to the total weight of the train, the sum is the total weight-equivalent of the train.

7. Train-resistance data were obtained by drift tests on level track. From these tests formulas were derived as follows:

For Interurban Electric, $R_t=\dfrac{V+45}{450}$

For Key System, $R_t=\dfrac{V+40}{1{,}000}$

in which R_t is the retardation in miles per hour per second caused by train resistance and V is the speed in miles per hour. The low train resistance of Key System equipment is a result of the installation of roller-bearing journals in all trucks.

8. Grades on the bridge railway vary from three per cent descending to four per cent ascending and lengths of blocks vary accordingly.

9. Resistance caused by track curvature was a factor in the calculation of our speed-time-distance charts, but its effect on braking was not of great importance and will not be discussed here.

To calculate the distance traveled from the initiation of a service brake application until the train is stopped, a second-by-second method is used. The retardation of the speed of a train, caused by the application of the brakes during a period of one second, is obtained by the formula

$$R_b=G\cdot r\cdot e\cdot p\cdot f$$

in which

G is the constant of acceleration caused by gravity in miles per hour per second, taken as 21.93

r is the nominal braking ratio, the ratio of the total nominal brake shoe pressures to the total weight-equivalent of the train

For the Interurban Electric fully-loaded ten-car train

$$r=\frac{1{,}130{,}400}{1{,}220{,}000+100{,}000}=0.856$$

For the ten-car light train of the preliminary tests

$$r=\frac{942{,}000}{970{,}000+100{,}000}=0.880$$

For the Key System fully loaded train with clasp brakes

$$r=\frac{1{,}057{,}700}{1{,}248{,}000+100{,}000}=0.785$$

and with single brakes

$$r=\frac{1{,}181{,}900}{1{,}206{,}000+100{,}000}=0.905$$

For the Key System light train with clasp brakes

$$r=\frac{1{,}057{,}700}{952{,}000+100{,}000}=1.006$$

with single brakes

$$r=\frac{1{,}181{,}900}{910{,}000+100{,}000}=1.170$$

e is the brake rigging efficiency taken as 0.85

p is the ratio of total effective pressure to total full pressure

f is the coefficient of friction for the second involved and is obtained by means of the nomograph, figure 3, after the average speed for that second and the average distance through which the brakes have been applied have been estimated

In the formula for R_b, G, r, and e are constant for a given train condition. For the fully loaded Interurban Electric train

$$G\cdot r\cdot e=21.93\times0.856\times0.85=16.0$$

and the formula for this train may be simplified to

$$R_b=16\cdot p\cdot f$$

The total retardation per second is equal to the retardation caused by braking, plus that caused by train resistance, plus that caused by grade, or

$$R=R_b+R_t+R_g$$

R_g is positive or negative in accordance as the grade is ascending or descending. The formula is

$$R_g=s\cdot G\cdot\frac{W}{W_e}$$

in which s is the grade, G is the gravity acceleration constant, W is the total weight, and W_e the total weight-equivalent of the train. For the loaded ten-car train on a three-per-cent descending grade

$$R_g=-0.03\times21.93\times\frac{1{,}220{,}000}{1{,}320{,}000}=-0.61$$

miles per hour per second.

In the typical calculations shown, symbols which have not been fully discussed are as follows:

V, speed, miles per hour, at the end of each second

V_a, average speed during the second

D, distance in feet traveled during the second

SD, total distance traveled since brake handle was placed in service position

d, equivalent distance $(D\cdot p)$ brakes were fully applied during the second

Sd, total equivalent distance brakes have been fully applied to end of second

Sd_a, total equivalent distance brakes have been fully applied to middle of second

After the final braking distance for a given speed and grade has been calculated and the required over-all length of the restrictive blocks obtained, the minimum length of a single block is found. On descending grades we have four restrictive blocks in the rear of the occupied block and three restrictive blocks where the grade is level or ascending. Our standard rail length is 39 feet and where practicable the block length is a multiple of 39 feet or of one-half of 39 feet.

In order to check the length of two blocks for braking from the 25 control, and of one block for the 17 control, calculations must also be made for braking from 27.54 and 18.87 miles per hour. For the project under discussion, braking distances were calculated for level grade, one, two, and three per cent descending, and one, two, and three per cent ascending grades.

In the typical tabulations shown, all calculations were made with slide rule. The formulas given herein for various functions of speed are not considered applicable to train speeds greater than 50 miles per hour.

A New Technique for Lead Cable Sheathing

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Synopsis: A new technique used in the production of lead sheaths for electric power cables is introduced. The various phases of the problem and the difficulties encountered heretofore are described. It has been found that it is necessary to consider the problem both as a mechanical and a chemical one. A method is described in which both factors are used. This consists in pretreating lead as received with a sodium-lead alloy to remove all deleterious impurities and the use of a special standpipe procedure for filling the lead-press extrusion cylinder to obtain a complete union of successive charges, resulting in sound lead sheaths throughout the entire cable length. Test data show that the physical and corrosion properties of lead are not adversely affected by the sodium treatment.

THE HISTORY of the cable-making art shows some very interesting facts. Twenty years, and more, ago, while the use of electric power in the United States was increasing rapidly and the electric power utilities were trying to meet the demand for the transmission of power with the installation of cables operating at higher voltage than heretofore used, they seemed to be held back because of the poor operating record of the cables furnished. A study of the situation showed it to be due to the nature of materials (paper and oil) used for insulation and the lack of proper drying, degasifying, and impregnation methods. In time, this situation was overcome and the rate of cable failures due to defective insulation decreased. However, with the improvement in the technique of insulation manufacture a new problem came to plague both the manufacturer and the cable user.

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This accomplishment has taken several years to bring to a successful conclusion and required the combined efforts of our production and technical staffs. Among the latter who co-operated in this development were H. L. Beede, technical manager; F. H. Gooding, research engineer; and E. Critchley, assistant chemist.

1. For all numbered references, see list at end of paper.

About 1931 an increase in cable failures due to the lead sheath was noted and this seemed to continue for several years, until today it is found that the major portion of inherent cable failures as reported by the Association of Edison Illuminating Companies and the Edison Electric Institute are due to defects in the lead sheath.

Recognition of the lead sheath as a source of trouble led to an intense investigation of the physical properties of lead as well as manufacturing methods of making lead pipe. As a result, we find some valuable papers written by Moore and his associates, of the University of Illinois,[1] McKeown,[2] and Waterhouse.[3]

The research staffs of the public utilities, such as Commonwealth Edison Company, Philadelphia Electric Company, and Detroit Edison Company, have reported at technical meetings from time to time on their studies. At the same time the cable manufacturers were spending large sums of money on the improvement of manufacturing methods as well as researches on the physical properties of lead as used in cable sheathing. Some of these have been published through technical organizations, such as Bassett and Snyder,[4] Phillips,[5] Dunsheath,[6] and others privately, such as Sherman.[7] All authors were interested in the physical properties of lead and have contributed to the knowledge of the action of lead under physical stress, yet it cannot be said that they advanced the solution of the lead-sheath problem as rapidly as desired. The influence of internal stresses on the expansion of the sheaths was widely studied but we still had the lead-sheath problem as distinct from lead in strip form.

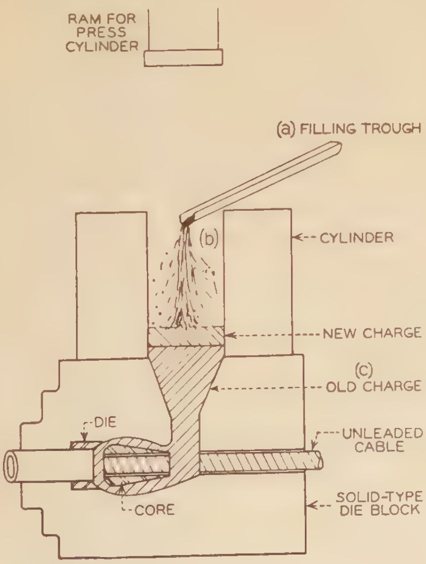

Figure 1. Trough filling of cylinder

The cable manufacturers gave serious study to the improvement in manufacture of lead sheaths. Various methods, mostly of a mechanical nature and referred to as "improved foundry practice," were tried out. Under this slogan we find the vacuum press,[8] in which the lead-press cylinder is filled with molten metal under conditions in which most of the air is eliminated; hydrogen flame,[9] where the metal is poured in the presence of burning hydrogen which reacts with the oxygen in the vicinity of the molten lead and prevents further surface oxidation of the molten metal; electric arc and oxyacetylene flame which melt the oxidized surface of the residual charge so as to assist in the union of the two charges; high density inert gas,[10] which is used to maintain a nonoxidizing gas blanket over the molten lead in the melting pot and to replace the normal atmosphere or air as far as possible during the time of pouring; continuous extrusion machines,[11] which have been developed in Europe in which the lead is never in contact with air. Mechanical difficulties have been encountered which have delayed the extensive use of this type of machine and at the present time it cannot be considered as a commercial lead press free of shortcomings. Our company studied the claims made for each of the above lead-press processes hoping to find a solution to the problem of elimination of flow lines and laminations in lead sheaths. Some of them appeared to have merit, others were fair, and some of no value. We were able to try all but the vacuum press and the continuous extrusion machine sufficiently long to make us feel that from our viewpoint they were not able to accomplish what we were seeking, namely, a continuously uniform cable sheath no matter how many cylinder charges were required which did not have critical regions, charge welds, or laminations.

A careful study of lead-pipe manufacture indicated that there are two distinct problems. One of these problems pertains to the method of filling the lead-press cylinder with new molten lead and the other deals with the chemical stability of the lead itself. These two problems are closely related and by solving both we have a means to obtain the desired end.

Figure 2 (left). Nonunion of charges

Figure 3. Cable sheath resulting from trough filling

Let us discuss first what happens when the cylinder of a lead press is filled. Figure 1 is a sketch showing the pouring of molten lead from the melting pot into the cylinder. The lead flows along a trough (*a*) to the cylinder and then splashes itself into a broken stream (*b*) as it fills the cylinder. A considerable amount of air becomes occluded and further oxidation of the hot lead takes place so that the cylinder of lead contains gas and lead oxides. Moreover, the previous charge (*c*) is solid and has a surface temperature of about 250 degrees Fahrenheit compared with that of 700 degrees Fahrenheit for the new lead. The incoming molten lead is chilled as it strikes the surface of the old lead, resulting in the condition shown in figure 2. The two charges are easily separated yet they are forced down through the lead block, around the core to form a lead sheath. Such a pipe is not a sound lead sheath, but contains flow lines, laminations, and poor welds, particularly in the so-called critical regions where the lead at the union between the two charges is extruded. If rings are cut along the pipe and etched, we find crystal structures, such as shown in figure 3, which clearly indicate flow lines full of inclusions. Such a pipe is none too strong and in time under stress will produce leaks. The electric arc, oxyacetylene flame, and continuous extrusion machines attempt to correct the nonuniting of charges. This is difficult to accomplish by the first two methods as the molten surface of the residual charge has already started to chill before the new lead reaches it. The continuous extrusion machine may have great promise but it is still in the development stage and many problems pertaining to the control of temperature in its various parts and the overcoming of severe oxidation within it if allowed to cool have yet to be solved.

Recognizing the importance of getting successive charges of lead to unite, we adopted the method developed by our associate company in England, Callender's Cable and Construction Company, Ltd., of bottom filling in which the molten lead is directed by means of a pipe to the surface of the previous charge. This eliminates the splashing that usually takes place, and therefore, the entrapping of air, at the same time causes the new hot lead to melt the surface of the previous charge while the cylinder is being filled and replaces the old charge with a mixture of new and old metal. This is known as the Hill standpipe[14] method of filling and is illustrated in figure 4. (*a*) is a pipe which is attached to the spout of the melting pot and guides the molten lead to the surface of the previous charge (*b*); by means of the handles (*c*) the end of the pipe is moved around by the operator so that all of the surface is subjected to the heat of the stream of the new lead and the old charge is completely replaced with a mixture of new and old metal. When the cylinder is filled with lead, the pipe is withdrawn, the surface is skimmed, and the ram is pressed against the lead during the time it takes to solidify the lead prior to extrusion. This results in a perfect uniting of the two charges, as shown in figure 5, which shows a half section of a slug removed from the press and a perfect joining of the lead. The remains of the old charge can be identified by the small-size grain structure resulting from the previous pressure cycles. Slabs may be cut from the other half and bent into a U shape without showing any splitting where the charges unite.

Although a better lead sheath than formerly was obtained, it was noted that there were oxides and other deleterious impurities still present in the lead as inclusions. Since inclusions are known to cause defects in cable sheaths, it is obvious that their complete elimination is desirable if it is intended to improve the quality of the lead pipe. We therefore studied various ways which have been pro-

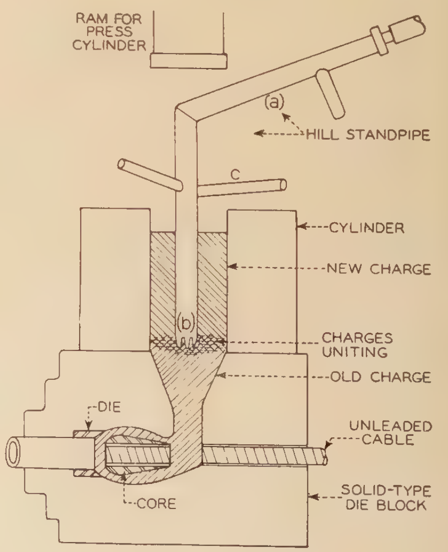

Figure 4. Hill standpipe method of filling cylinder

posed to remove entrapped impurities in lead. While the vacuum press will remove free gases during the filling of the cylinder and thus eliminate oxidation in this respect, it cannot reduce entangled oxides, decompose sulfides, or eliminate other deleterious impurities already present in the lead in the melting pot; such impurities are to some extent soluble in and occluded by the molten metal.[11–13] The impurities segregate themselves between the lead crystals and thus weakness and corrosion along crystal boundaries results. When cooling is rapid as in the case of the molten metal while being transferred from the melting pot into the lead-press cylinder, the impurities have no time to separate, and are therefore interspersed throughout the mass and not merely at the so-called critical region. Furthermore, the deleterious impurities are not only detrimental in themselves, but they also bring about a condition whereby small amounts of oxidation products act as catalysts and thus there is a possible progressive acceleration of oxidation and decomposition taking place in the melting pot.

When commercial lead is melted, the dross removed, and then remelted, the tendency for dross formation in the molten state will be as before. D. M. Smith[13] has shown that on melting lead in a vacuum of the order of 0.025–0.015 millimeter mercury pressure, dross appeared on the surface and increased in quantity on agitation of the molten metal. Two or three purifications under vacuum were necessary to practically prevent continued dross formation.

As stated above, the use of a hydrogen flame to reduce the oxides as the lead is poured into the cylinder is not completely effective. The flame contacts only the surface of the stream of molten metal, and, therefore, merely prevents further oxidation without helping the situation. This method alone does not bring about complete union of charges.

While the surface of the residual charge can be melted by the electric arc or oxyacetylene flame, the oxides originally present will only be disturbed but not removed. When pouring the new charge of lead at the usual pouring temperature, which is around 750–775 degrees Fahrenheit, there will not be sufficient fluidity or residual heat to allow those oxides, sulphides, and other deleterious impurities which are insoluble in molten lead to rise to the surface and be skimmed off.

Figure 6. Cable sheath resulting from Hill standpipe filling

The use of inert or reducing gases in the lead-press cylinder is ineffective as the release of the gas under pressure has a cooling effect on the molten metal entering the cylinder. The lowered temperature and marked sluggishness of the molten lead prevents proper welding between charges. Moreover, the oxides in solution which are always present in molten metal are unaffected. Besides, foaming of the molten metal and occlusion of some of the gas takes place, thus bringing about blistering, gas pockets, and sponginess in the extruded sheath. Even when inert gas is used with a positive pressure over the melting pot, dross with an appreciable amount of red lead accumulates. The other methods referred to all suffer from similar difficulties.

Apart from the many efforts to bring about some sort of stability to the molten lead as it enters the lead-press cylinder, various means have been employed to reduce as far as possible surface oxidation of the molten lead in the melting pot. Such ingredients as burnt clay, sand, powdered mica, charcoal, graphite, fluxes, various salts, and mechanical contrivances have been used. Stabilization of lead has also been attempted under different circumstances, using chlorine, phosphorus, boron trichloride, titanium tetrachloride, vanadium trioxide, lithium, and a host of other reducing and deoxidizing substances. In all such cases the reagents failed to bring about the desired results.

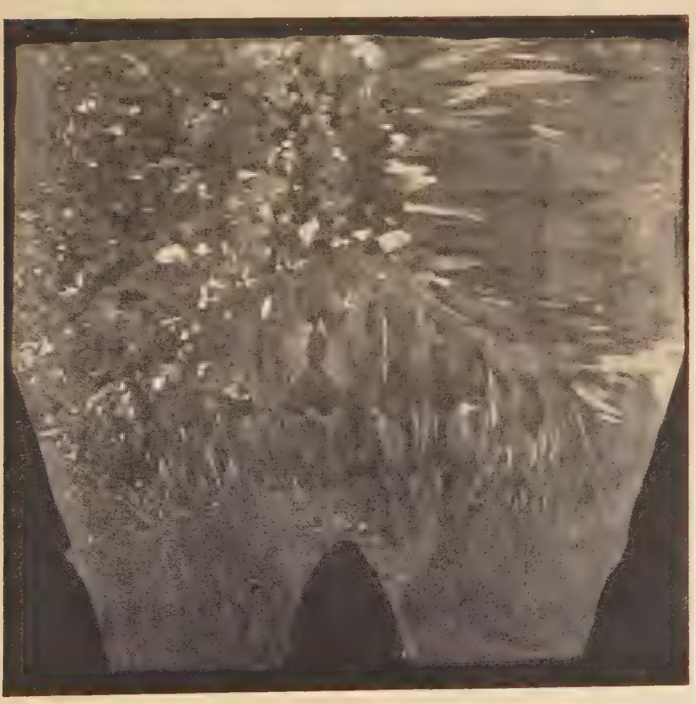

Figure 5. Complete union of charges

Recognizing the shortcomings of all the

methods in use for the stabilization of lead, we proceeded to experiment with various deoxidizing and reacting substances so that the treated metal may not only be free from occluded oxygen and

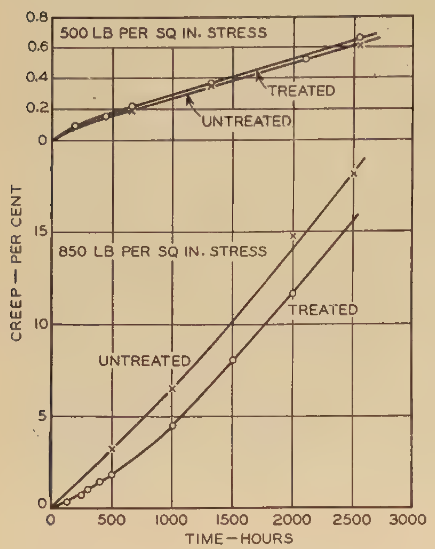

Figure 7. Creep tests on lead strips cut from cable sheathing

Temperature 15 degrees centigrade

other gases, but also free of entangled oxides, sulphides, and other deleterious impurities; moreover, that after the elimination of all such impurities, the treated metal should be immune from further oxidation and contamination in process of extrusion.

After conducting a research extending over a period of several years, it was found that the desired end could be accomplished by the chemical stabilization of lead and its alloys. The active reagent that brings about this stabilization is metallic sodium, a member of the alkali metals in the periodic group, preceded by lithium and followed by potassium. Sodium, when used within critical limits and under prescribed conditions, stabilizes lead without at the same time changing the basic physical characteristics or affecting adversely the corrosion-resistant properties of the treated metal. It can be obtained as a relatively stable alloy of lead and is commercially available at a reasonable price. Since metallic sodium is quite reactive and dangerous to handle under atmospheric conditions, apart from the fact that uniformity of treatment is difficult, it is necessary to alloy it under controlled conditions with lead and this alloy is then introduced into the lead to be stabilized.

The amount of master alloy to use depends upon the kind of lead to be treated and the impurities present in the metal as received from the refinery. For example, as little as 0.005 per cent of metallic sodium cleanses, and as a result imparts a silvery color to electrolytic lead. This type of lead, which is known to dross more than any other commercial lead on the market, may then be heated at elevated temperatures for long periods of time in an open pot without contamination.

The critical amount of sodium used in this treatment of lead ranges from 0.005 per cent to 0.05 per cent by weight of the amount of lead being treated. Upon the addition of the sodium-lead alloy to the molten lead, the alloy is broken down into its component parts at a temperature of 850–900 degrees Fahrenheit. The sodium thus released combines with any free or dissolved oxygen, reduces the various oxides, and decomposes as well as throws out of solution such deleterious compounds as sulphides which are usually present in commercial lead. The deleterious impurities thus released float to the top of the molten mass of metal from which they are readily skimmed off.

This method of treatment results in a trace of sodium of the order of 0.001 per cent remaining in the lead. This small amount of residual sodium has a stabilizing effect upon the treated lead in that the latter may be allowed to solidify, then remelted without the necessity of again treating with sodium-lead alloy. The remelted lead not only does not dross, but retains the same silvery appearance and physical characteristics as the lead resulting from the first treatment.

It is possible to keep the treated lead, due to its stability, at temperatures as high as 850–900 degrees Fahrenheit in the melting pot for long periods of time without fear of dross formation and without affecting the physical characteristics of the extruded metal. This treatment overcomes the natural sluggishness of lead and its alloys at any given temperature below red heat. The increase in fluidity of the molten metal together with the higher pouring temperature is a distinct advantage, as it not only helps to float to the surface any foreign matter which might find its way into the cylinder, but also facilitates the fusion and welding of the old with the new charge.

For lead alloys, the lead is first pretreated and then the alloying metal, as

Figure 8. Increase in pipe volume due to steady internal pressure of 62 pounds per square inch (500 pounds per square inch hoop stress)

Temperature 25 degrees centigrade

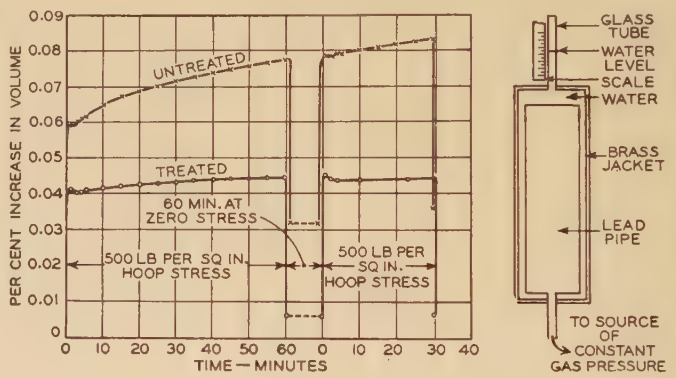

Table I. Physical Tests

	Tensile Strength* (Pounds per Square Inch)	Elongation (Per Cent in One Inch)	Rockwell Hardness Number **	90-Deg Bends Original IPCEA† Machine
Electrolytic				
Untreated	1,980	75	62	88
Treated	2,010	83–87	65–67	72–84
St. Joseph (0.06 per cent copper)				
Untreated	2,350	66	72.5	50–66
Treated	2,280	78–78.5	72.5	58–66
Electrolytic and 0.01 per cent lithium				
Untreated	2,680	58	92.6	27
Treated	2,890	65	88	27
St. Joseph and 2 per cent tin				
Untreated	3,140	62.5	85.2	24
Treated	2,980	72	75	22

* Speed of machine one inch per minute.

** Model *R H*, one-half-inch ball penetrator, 30-kilogram load. Anvil 3/8-inch flat spot. Time factor 30 seconds.

† Insulated Power Cable Engineers Association.

Table II. Bend Tests

Type of Lead	Time of Test	Single 90-Deg Bends, IPCEA Machine: Average	Maximum	Minimum
Electrolytic	Immediately	50	72	40
	One week later	78	100	56
	Two years later	92	106	78
St. Joseph	Immediately	52	78	42
	One week later	76	90	60
	Two years later	89	100	78

such, or in the form of a master alloy, is added. Here also, it is possible to maintain a high temperature in the melting pot. The extruded alloy sheath shows uniform dispersion of the alloying metal and is free from inclusions or laminations.

Although our method of treatment consists in taking a mixture of lead and sodium, which we call the master alloy, and dissolving it in the molten lead to be treated, we do not get as a result an alloy of lead in the final product.

To determine what influence the treatment has on the physical and corrosion-resistance properties of lead, experiments were conducted on both types for comparison. Table I shows typical physical properties for several types of lead and lead alloys.

Taking bend tests[8] as an indication of aging, table II shows the change in two kinds of treated lead immediately, one week, and two years after extrusion. It is to be noted that recrystallization or self-annealing has taken place and the range between maximum and minimum bends are closer after two years than when first tested, which is typical of commercial lead.

Creep tests on treated and untreated lead strips, and expansion tests on pipe have indicated that the treated lead is somewhat superior in resisting distortion due to stress even when the standpipe method of filling the cylinder is used in both instances.

Figure 7 shows the results of creep tests made at 500 and at 850 pounds per square inch. At 500 pounds per square inch there is practically no difference, but at 850 pounds per square inch the untreated lead stretches faster than the treated metal. This might be expected because of the improved crystal bond that is characteristic of the treated lead, and which reduces that part of the flow which is associated with the crystal boundaries.

Expansion tests were made on samples of lead pipe, sealed at the ends, and subjected to internal pressure. The increase in volume of the pipe was measured by the water displacement method shown at the top of figure 8. The initial creep and creep rate and the elastic recovery when stress is removed are shown for a 62-pound-per-square-inch (500 pounds per square inch hoop stress) pressure cycle, lasting one hour. This is followed by a one-hour zero-pressure period and a further one-half hour stress period. The initial creep and creep rate are greater for the untreated lead. The recrystallization during the one-hour rest period was negligible in both cases.

Stress-strain curves, made on similar samples of lead pipe, exhibited the same tendencies, see figure 9. The pressure was raised by 10-pound steps, and the increase in volume noted at each step. At 50 pounds per square inch the untreated pipe began to expand rapidly, and had reached the short-time yield point. The treated pipe went to 70 pounds per square inch before this point was reached.

The combination of the Hill standpipe method of filling the lead cylinder and the use of treated lead has resulted in an improved quality of lead sheath. Several years ago, while making the study of the various methods proposed for obtaining better sheaths, it was realized that to appreciate the full value of any improvement in lead-press technique it was necessary to test full-charge lengths of pipe, extruded under normal production conditions, instead of short specimens. Therefore, a time-pressure test was set up by taking full-charge lengths having about 2.80 inches outside diameter and 0.141 inch wall. Both ends are sealed and an internal pressure of 90 pounds per square inch of air (805 pounds per square inch circumferential stress) is applied for ten days and then the pressure increased 10 pounds per square inch internal pressure every five days until rupture occurs. The early tests with former process resulted in many of the samples failing on the first step and usually on a charge weld, or close to a die weld, where the tongues of the flow lines were very pronounced, resulting in blunt fractures. With the new technique the pressure reached on the average the 130 pounds per square inch step internal pressure (1,160 pounds per square inch circumferential stress) before rupturing which normally occurs at the thinnest part of the sheath and with a clean knife-edge fracture. Figures 10 and 11 show the rupture of lead pipes made by the old and new methods. Monthly checks are made on full-charge lengths from regular factory production runs and

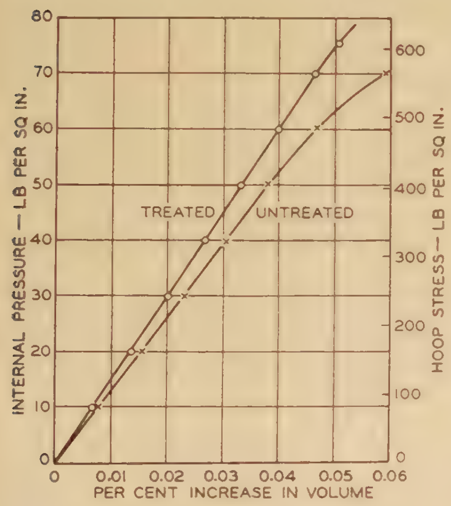

Figure 9. Increase in pipe volume due to rising internal pressure

Pressure increased at ten pounds per square inch per ten seconds

Temperature 25 degrees centigrade

Figure 10. Pressure-test rupture of pipe made by old method

Figure 11. Pressure-test rupture of pipe made by new technique

after bursting the fracture is examined for location along the pipe, the position with respect to the welds, the nature of the fracture, and the uniformity of crystal size. In addition, a slug of lead from each press, following the extrusion of the pipe, is cut in sections and etched as shown in figure 5 as a check on the technique of cylinder filling.

This technique of filling the cylinder completely eliminates the so-called critical region from a pipe. Figure 6 shows an etching of a ring taken about 30 feet from the beginning of a pipe and in the zone of what is normally considered the critical region. When compared to figure 3 one readily notes an improvement.

Table III. Chemical Corrosion

Time in Hours in Boiling Distilled Water	Type of Lead Sheath, Specimen Approximately 150 Grams		Milligrams $Pb(OH)_2$ per Gram of Lead
25	St. Joseph	Untreated	0.049
		Treated	0.027
70	St. Joseph	Untreated	0.064
		Treated	0.042
112	St. Joseph	Untreated	0.089
		Treated	0.068

In view of the intense chemical activity of metallic sodium in the presence of moisture or chemical solutions which are known to attack lead, comparative corrosion tests were conducted on treated and untreated metal. Since corrosion is largely of an intercrystalline nature the extent of corrosion will, in a measure, depend upon the purity and general characteristics of the intercrystalline material, or we may say the cementing medium. According to Dunsheath,[6] this cementing medium is generally made up both of amorphous and crystalline metal, with the former predominating. It is this boundary material which is readily susceptible to corrosive conditions, particularly when the metal is under stress.[6] Since sodium treatment brings about stabilization not only to the crystals but also to the intercrystalline cement as well, it is expected that better bonding between crystals, greater stability, and less susceptibility to corrosion should result.

A series of corrosion tests were made to compare the rate and degree of corrosion on treated and untreated lead. Both types of lead were exposed to live steam at 105 degrees centigrade for 100 hours. The treated lead disclosed a white deposit of lead hydrate, $Pb(OH)_2$, which could be readily rubbed off. The untreated lead had a brownish white deposit on the surface which was hydrated lead monoxide $PbO.Pb(OH)_2$. The latter was quite pronounced, embedded in the surface, and required a sharp tool to remove it.

In another experiment 2-inch squares of lead sheath, approximately 150 grams in weight, after being thoroughly sandpapered, washed with distilled water, and wiped dry with a soft cloth, were placed in 500-cubic-centimeter porcelain casseroles, submerged in 300 cubic centimeters of distilled water, and boiled for varying periods of time, ranging from 25 to 112 hours. At the end of the respective periods the solutions were tested for alkalinity by titrating with a one-tenth normal solution of HCl, using phenolphthalein as an indicator, and calculated to milligrams of $Pb(OH)_2$ per gram of lead. The results are shown in table III.

It is to be noted that in all cases the water for the untreated lead showed a greater alkalinity than the treated lead. Moreover, when the samples were removed from the casseroles and allowed to dry, the deposit formed on the surface of the untreated lead samples was more pronounced and was whiter in color than on the treated samples.

In addition, corrosion tests were made on samples of both types of lead by differential aeration, using various kinds of chemical solutions which are known to be met in actual service. Nine samples of lead pipe, 1.75 inches over-all diameter and 6 inches long, with the solutions were placed in one-quart glass jars and the pipes were partially submerged by setting the jars in an inclined position. The results of these corrosion experiments as indicated by the amount of acid necessary to neutralize the resulting alkalinity of the solutions are shown in table IV.

Table IV. Corrosion Due to Differential Aeration

Description of Solution	Cubic Centimeters of 0.066 n HCl Used to Neutralize Ten Cubic Centimeters of Solution: Untreated Lead	Treated Lead
Manhole water	0.3	0.3
Manhole water plus CO_2	0.9	0.55
Tap water plus CO_2	0.3	0.3
Tap water plus CO_2 plus one per cent acetic acid	47.5	45.0
$n/10$ sodium bicarbonate	15.4	15.2
$n/10$ sodium chloride	1.3	0.3
$n/10$ calcium sulphate	1.9	0.8
$n/10$ ammonium hydroxide	7.7	6.7
One per cent lime water	8.0	7.6

It is to be noted that when comparing both types of lead that the treated lead does not show any greater degree of corrosion than the untreated lead.

Considering the results of the experiments described above, it is our opinion that the corrosion resistance of treated lead is at least equal to, and somewhat better than, that of untreated lead.

Summary and Conclusions

The following conclusions may be listed as to what has been accomplished by the combination of the method of filling which we are using and the stabilization of the lead.

1. All types of deleterious impurities are removed in process of treating commercial lead with sodium within the critical range of 0.005 to 0.05 per cent sodium. Such treated lead will retain approximately 0.001 per cent residual sodium which has a stabilizing effect, when such metal is remelted, processed, and used in service.

2. In processing no special equipment is necessary, no extraordinary ingenuity is required, and no hazard in treating lead is involved.

3. With proper lead-press procedure, cable sheaths extruded from treated lead disclose a bright appearance, a distinct, uniform, and brilliant crystal structure, absence of flow lines, inclusions, and other commonly known defects.

4. Alloys prepared from treated lead are homogeneous and stable; moreover, the tendency toward segregation is reduced and thus greater resistance to corrosion is brought about.

5. Chemical corrosion tests show treated lead to be somewhat better than untreated lead.

6. Cable sheath extruded from treated commercial lead is in conformity with American Society for Testing Materials and Association of Edison Illuminating Companies requirements.

7. A cable sheath of stabilized metal is available, which throughout its entire length is free of occluded and dissolved gases, various oxides, sulphides, and other foreign matter.

8. A stabilized cable sheath has been developed whose metal can be remelted and maintained at elevated temperatures, such as 900 degrees Fahrenheit, in an open pot for long periods of time without drossing or affecting its chemical or physical characteristics.

9. By means of treated lead and bottom filling as carried out with the Hill standpipe complete welding of charges is assured.

10. The appreciably greater fluidity and higher temperature of treated metal is a distinct advantage as it not only helps to float to the top of the lead-press cylinder any foreign matter, but makes it much easier to fuse the old and new charges and thus facilitates the welding operation.

11. In the long-time pressure test on full-charge lengths, treated lead sheaths require invariably a higher pressure and disclose a knife-edge break at time of rupture.

12. It cannot be overemphasized that the lead-sheath problem is both a mechanical and chemical one. If improved quality of lead sheaths is to be expected, then our method, or some other method that will bring about the same result, is necessary.

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Discussion

Lyall Zickrick (General Electric Company, Schenectady, N. Y.): I have studied with quite some interest the preprint copy of the paper "A New Technique for Lead Cable Sheathing" by Reinitz and Wiseman.

The authors are to be commended for their efforts and endeavor in attempting new improvements for the cable manufacturing industry. There are contained in the paper, however, several items which it would be well to have the authors further clarify. For convenience, these items may be listed as follows and taken up in detail:

(*a*). References to the work of other investigators.

(*b*). Comments on the method of filling.

(*c*). Regarding quality of lead and effect of sodium.

(*a*). In the authors' references to the work of other investigators it appears that considerable detail has been omitted from the report which would justify their conclusions. Inasmuch as these references to the work of others are quite critical, substantiating data would seem desirable. I know in our work with hydrogen there are both effective and ineffective ways in which it may be applied. There is no doubt about the ability of hydrogen to reduce lead oxide when applied correctly.

(*b*). In reading the description of their method of filling, I have been wondering if the authors experience any difficulty in getting a good well-fused area between the new and old charge. We were successful with some of our early methods in obtaining a well-fused area in the central portion, but not clear to the edge. We now obtain an excellent bond clear to the edge and for about three to four inches into the old charge.

Table I

	Per Cent		
	(A) Southeast Missouri Desilverized Lead	(B) Very Pure Lead	(C) Southeast Missouri Undesilverized Lead
Silver	0.0004	0.00000	0.0068
Arsenic	0.0001	0.0000	0.0000
Antimony	0.0012	0.00024	0.0010
Bismuth	0.0012	0.0000	0.0005
Copper	0.0003	0.000057	0.062
Iron	0.0008	0.000193	0.0003
Zinc	0.0007	0.000080	0.0002
Manganese	0.0000	0.0000	0.0000
Nickel and cobalt	0.0000	0.0000	0.0048
Total of above impurities	0.0047	0.000570	0.0756
Lead by difference	99.9953	99.99943	99.9244

(*c*). Throughout the text there are a great many references made to the quality of pig lead which appear to be quite alarming. One gains the impression that the so-called good brands of lead we cable manufacturers use are full of, to quote: "entangled oxides, sulphides, and other deleterious impurities", and again "such deleterious compounds as sulphides which are usually present in commercial lead", and still again I encounter the phrase, "the oxides in solution."

I feel it would be especially desirable for additional enlightenment on this subject, for if such is the quality of lead we use, the industry should be so informed.

For my own part, I have never found any evidence of any solubility of oxides in lead, either in the literature or elsewhere, and the same is true as well for sulphides. If these so-called impurities are soluble, I would not expect them to segregate, especially to the grain boundaries as stated, at least until they had precipitated from solution.

Again in the text an implication has been made which suggests an excessive amount of dross in pig lead. Reference 13 to the work of D. M. Smith has been quoted. Smith's work gives no information whatsoever as to the source, type, or chemical composition of the lead he used, but merely states that upon melting in vacuum he obtained a quantity of dross, which to quote directly from his work: "Spectrographic analysis showed that this dross consisted mainly of lead, small quantities of tin, calcium, aluminum, magnesium, cadmium, and carbon also being detected." It does not appear reasonable to classify the above as being in any way representative of our pig lead of the present day, produced by reliable refineries. I believe the lead we use is of far better quality than is herein intimated.

I am somewhat confused as to the part or metallurgical function the sodium addition plays, especially the residual sodium.

In general, I believe it is accepted that the purer the lead is the lower the tensile properties, and also to a degree the larger will be the grain size and the lower the resistance to fatigue. For illustration, the data in tables I and II of this discussion are pertinent ("Pure and Low-Alloy Lead", a paper by G. O. Hiers presented at an AIME symposium on pure metals, February 1939).

In table II you will note the low physical properties for lead 99.9994 per cent pure. If such is the case, the action of this small amount of residual sodium scarcely seems to be in the direction of greater purity.

Again I read "untreated lead stretches faster than the treated metal because of the improved crystal bond that is characteristic of the treated lead, which reduces that part of the flow which is associated with the crystal boundaries."

Table II. Hardness and Tension Tests of Cast Metal

	(A) Southeast Missouri Desilverized (7)	(B) Very Pure Lead 3712(5)	(C) Chemical Lead (10)
Yield point (0.5 per cent elongation) (pounds per square inch)	861	714	1,643
Ultimate tensile strength (pounds per square inch)	1,966	1,609	2,765
Elongation (per cent)	64.2	68.6	50.2
Reduction in area (per cent)	92.4	100.0	87.9
Brinell hardness number one hour after casting	4.2	2.9	5.5
Brinell hardness number ten days after casting	4.1	3.0	5.4

In metallurgy the nature of crystal boundaries and their characteristics has for years been a subject for controversial argument and discussion. It seems the subject can hardly be so easily and lightly dispensed with. The inference is that lead flows along crystal boundaries at least to a degree, and because of this treatment such flow is retarded. It is common metallurgical knowledge today that the precipitation of a phase from solution causes such a stiffening of crystal boundaries, so here again a higher degree of lead purity is not indicated. Precipitation may occur throughout the crystal,

but time and aging tend to agglomerate the precipitated phase in the grain boundaries. Could not this strengthening effect be due to precipitation of a sodium-lead phase originating from the residual sodium? Long-time aging tests (two years or more) taken on sheaths containing varying amounts of residual sodium should give important data covering the effect of this constituent on fatigue, corrosion resistance, and other physical properties.

Herman Halperin (Commonwealth Edison Company, Chicago, Ill.): For a given kind of lead or lead alloy, the two main desirable characteristics of the sheath from the standpoint of the user are (*a*) soundness of structure and (*b*) circumferential uniformity of thickness. The authors' paper relates to the first characteristic.

As indicated in my discussion on expansion of sheaths on underground power cables in service in the University of Illinois Bulletin 306 mentioned in reference 1 of the authors' paper, imperfect welds and nonmetallic inclusions usually constitute the initial set of causes for a large number of openings of sheaths at defects in service. After about five years of operation, openings have occurred in Chicago at a high rate also in abnormally thin portions of sheaths. Most of these unfortunate occurrences in Chicago obtained for 66-kv solid-type single-conductor cable, the number of defective lengths of this type of cable involved having been close to 200 to date. Over 4,000 lengths of such cable were installed, principally during the period of 1926–31, inclusive.

Sheath troubles due to inherent defects have also occurred to a lesser extent with, for example, 4- and 12-kv cables which have relatively less insulation. Also, such cables have joints filled with a heavy viscous compound whereas the 66-kv cable had joints filled with a thin oil under a small pressure. The oil migrated into the cable and resulted in the maintenance of relatively high internal pressures during the periods of daily maximum loads. The resulting rate of sheath expansion has been excessive (about six mils in diameter per year) and so investigations are being conducted to devise a scheme to reduce sharply this rate in order that a reasonable cable life may be obtained.

In view of all our trouble, it is obviously very gratifying to have learned of the improvements described in the paper. Cable with sheath treated as outlined in the paper has been furnished to Commonwealth Edison Company and no structural defects have been found in such sheaths.

The authors refer to tests to rupture and to creep tests at 500 and 850 pounds per square inch. Such data are of general interest, but more pertinent data are those obtained at lower stresses which apply for most operation. Obviously, a sheath that expands unduly is quite undesirable and the cable may develop trouble long before rupture of the sheath occurs. The authors, I believe, appreciate this point because the manufacturer has co-operated with me by furnishing samples for long-time creep tests to be made at the University of Illinois under the sponsorship of the Utilities Research Commission. In these tests of treated lead, the samples of ASTM grade II lead and of ASTM grade III lead had creep rates within the range found for similar materials having no treatment.

Perhaps a word should be said also for some of the other developments on cable sheath. We have had a large operating experience and have obtained a large amount of test data on samples of such sheaths furnished by other manufacturers. The progress made by the various manufacturers toward always furnishing sheaths that are structurally sound has varied, but nowadays it appears that very good sheaths are being produced by some of the methods that the authors tried and found wanting.

Any of the methods used by the manufacturers must be accompanied by continuous good workmanship to assure uniformly perfect sheath structure, and the cable manufacturers are aware of this fact.

I. T. Faucett (General Cable Corporation, New York, N. Y.): The authors cover a very broad subject on which the industry has made large expenditures in research and development during the past decade. Essentially, the method which they recommend for obtaining uniformity of lead structure is to offset the effect of one impurity by the introduction of another. It would seem that the preferred approach to the problem is to exclude the impurities in the first instance, as is done, for example, in the vacuum press.

Among the recognized causes of field troubles with lead sheaths is the oxidation of ram lubricant. This is not mentioned in the paper, and it would be very interesting to know how this dangerous impurity is eliminated in the authors' process.

Another cause of trouble with lead sheath, common to most methods, is the chilling of the lead ram, molten lead, and cylinder walls during the charging of the press, as well as the oxidation incident thereto. As the ram moves out of the cylinder, air is allowed to enter and this not only chills the ram and cylinder walls but also chills and oxidizes the surface of the lead remaining from the previous charge. The Hill standpipe method, used by the authors, is subject to the above condition. The vacuum press, on the other hand, eliminates this source of trouble by providing a closed evacuated system into which the lead is introduced through an electrically heated pipe. In the vacuum press, oxide is not given a chance to form, whereas the authors' method depends upon the reduction by means of sodium of the oxides which must inevitably form and the subsequent skimming of the sodium oxide, which is not positive.

The authors refer to the vacuum press and state that:

> ". . . . while the vacuum press will remove free gases during the filling of the cylinder and thus eliminate oxidation in this respect, it cannot reduce entangled oxides, decompose sulphides, or eliminate other deleterious impurities already present in the lead in the melting pot. Such impurities are to some extent soluble in and occluded by the molten metal."

The authors state they have not investigated the vacuum press and apparently they are unaware of the method used in the melting of the lead in the lead kettle and the drawing of the melted lead into the lead cylinder. In the vacuum press the lead is melted in a basket located one-quarter of the height of the kettle from the top and the lead is drawn out at the center line of the kettle one-quarter of its height from the bottom. This procedure prevents any entangled oxides and other insoluble impurities from being carried toward the bottom of the kettle, because such impurities, due to their lower density, will float and further, because the melting is done at the top of the kettle. With this arrangement only pure bright metal can go over into the lead-press cylinder.

With further reference to entangled oxides and sulphides, it should be noted that the alkalies used in standard refining methods are as effective in removing sulphur as is the sodium treatment. This, together with information from precise tests, shows that sulphides are not part of the impurities unless incompletely refined or contaminated lead is used. As for the presence of oxygen, some of the leading metallurgists contend that it is not present in significant quantities. However, even granting that the sodium reduces or removes in the melting pot dissolved or occluded oxides, it would seem from the authors' description of their process that the molten lead must again be pretty thoroughly exposed to the action of the air and with a new opportunity to entrain or occlude oxides. How is this prevented unless there is present in the final metal considerable controlled amounts of sodium? Is 0.001 per cent of sodium supposed to be adequate for this, and, if it acts in this way, does it continue to exist in that quantity, regardless of detail of procedure?

The authors state that although sodium is present in the final product, it does not become alloyed with the lead. This statement is open to question, as metallurgical literature indicates that sodium may be in solid solution in lead in quantities comparable to those used by the authors. However, whether the sodium is present as an alloy or as a mixture, a much more careful and complete study of physical and chemical properties than is indicated by the authors seems warranted. Concerning the chemical properties, it is interesting to note that the authors conclude that their corrosion tests are favorable. In the long run, extended field experience will be the only sound criterion, particularly as there are so many factors influencing corrosion, other than those investigated by the authors. In particular, there must be assurance that the corrosion data obtained are with samples containing the maximum amount of sodium which may ever be present in actual commercial production.

The authors' test results are a case in point. It is noted that the treated lead had a white deposit which was readily rubbed off, whereas the deposit on the untreated lead had to be removed with a sharp tool. Contrary to accepted belief, this is suggested as an advantage of the treated lead. Lead owes its corrosion resistance to the formation on its surface of an adherent nonsoluble protective film. Chemical corrosion of lead in service occurs only where the conditions are such that the film is either soluble or nonadherent. It would be of interest if the authors would offer some explanation concerning their apparent belief as to the advantage over a strongly adherent film of one which could readily be rubbed off.

Data are given for tensile strength, elongation, hardness, bending tests, corrosion, and creep. Most of the differences shown are within the degree of experimental error

found in such tests and are not therefore of any importance other than to show that in these samples the sodium has not impaired the physical characteristics of the lead. As with other metals, the physical properties (ultimate state of equilibrium) of lead are affected by previous physical and thermal history and therefore some variation in these properties in different samples must be discounted unless the treatment of the lead is adequately controlled. On the other hand, if definite changes in the properties of the lead were found, may not these be due to the effect of the sodium as an alloy? If the change is due to the presence of the sodium, how do the properties depend upon the amount of this alloying constituent?

The condition shown in figure 10 is, we believe, not pertinent to present-day practice. With the condition of the nonunion of charges shown in figure 2 and the microstructure of extruded pipe shown in figure 3, it is natural to expect the rupture in the weld shown in figure 10. However, although these conditions may have existed five or six years ago, they are not representative of present-day practice and are definitely not those found in pipe made by many of the methods discussed by the authors.

The authors in their conclusions 3 and 4 state in effect that the structure of lead sheaths produced by their method is uniform and free from flow lines, also that the tendency toward segregation is reduced. It should be borne in mind that structural uniformity and freedom from flow lines are entirely relative, that is, some extrusion processes will result in less prominent flow lines than others, but in all cases flow lines and welds in the charge-weld region can be detected by proper etching methods. Flow lines and welds do not mean that the sheath is defective and tests prove that unless foreign inclusions or dimensional deficiencies are present, the weld usually will be as strong as the metal outside the weld region.

Bearing on etching methods, some experience which we have had in examination of lead sheets containing small quantities of sodium may be mentioned. So far as concerns ordinary behavior in the laboratory, this lead seems to tarnish no more and no less than similar lead without sodium. However, attempts to produce photographs of etched surfaces of lead containing sodium have met with great difficulty due to the tendency of the etched surface to tarnish much more rapidly than with any other lead or lead alloy with which we have worked. Because of this tarnishing or oxidation, photographs of the etched surfaces could be obtained only by a more refined etching technique than required for other lead surfaces.

A word on the control of the process is in order. Definite and simple control is of paramount importance in order to insure perfection in any product. With the vacuum lead press, control is very simple, since a vacuum gauge tells the whole story. If the vacuum is good, the results must be good. In the authors' method, however, the matter of control seems to offer great complications. In this connection, the following points may be considered:

(*a*). The authors indicate that a range of 0.005 to 0.05 per cent of sodium by weight (0.06 to 0.6 per cent by volume) may be used depending upon the impurities of the lead to be treated. Has any precise method been worked out to predetermine the amount required for lead from different sources and containing different impurities?

(*b*). What is the effect on the stabilizing properties if the sodium as poured into the press, varies from the normal amount?

(*c*). Have the studies of the physical and corrosion properties of the extruded lead been correlated with the final amounts of contained sodium or have these studies shown that the control of the amount of sodium used is unimportant?

(*d*). Figure 4 indicates that no means are provided to prevent air from entering the standpipe and to keep the pipe full of lead. Are such means provided? If not, is there not thorough mixing of the lead stream with air during the flow? Will not oxides formed be carried down to the bottom of the charge where they may be caught on the cylinder walls before rising to the top? Does the standpipe remain clean and bright, or does dross from the surface of the poured lead cling to it as it is removed?

D. M. Simmons (General Cable Corporation, New York, N. Y.): I like this Reinitz-Wiseman paper because it is such good publicity for the vacuum press which has been developed and is used by our company in all our paper cable plants. Moreover, the processes described in this paper actually do result in fairly good lead sheathing—though not, we are confident, as good as is obtained with the vacuum press. Consequently, in criticizing parts of this paper, the criticism is made not with the thought of unfavorable comment upon the resultant product, but rather is the criticism directed toward some of the theory and analysis, and toward some of the criticisms of other methods.

These authors have contrasted their present results with the worst results obtained in the past, obtained by methods now generally abandoned, and they would lead the reader to understand that only with their method can good results be obtained. The analysis by which they attempt, in the absence of experimental information, to establish this conclusion is the object of our criticism. Several different aspects of their analyses will be considered.

They describe the use of sodium in connection with lead which they describe as being very bad in respect to dross formation. They have apparently not recognized that excessive dross formation on lead is likely to be a result of contamination by certain metallic impurities present in exceedingly small amounts, such as antimony, etc. The sodium treatment, in addition to reducing the lead oxide formed on the outside of the pigs, happens also to be an effective means of eliminating these troublesome metallic contaminations. The rate of dross formation is so greatly reduced that, by contrast, the metal may, now, seem to retain a silvery surface. Also there may be enough sodium hydroxide formed to contribute a colorless slag still further helping to maintain a bright surface. The "stabilization" of the lead in the melting pot is thus very simply explained.

If these authors were using a lead with such bad drossing characteristics and were using this under conditions such as were common in lead covering some years ago, it is not surprising that there was excessive dross formation and excessive oxide inclusions in the sheath which was produced. The Hill standpipe method would not eliminate the formation of dross as the lead was passed into the cylinder and the excessive dross formed in the melting kettle itself may have found its way into the lead press. Accordingly, there was an exceedingly bad condition which undoubtedly was relieved considerably by the refining operation which this particular lead demanded.

Also, in reference to the appearance of the pigs of remelted lead, it should be noted that commercial lead is normally stored outdoors and subject to considerable surface oxidation and that any properly remelted lead stored inside will be much brighter and more silvery in appearance and will remain much brighter than commercially handled pigs as long as this lead is protected indoors.

Published data indicating the presence of appreciable amounts of oxygen in lead are not accepted by some of the best authorities on the metallurgy of lead. Also, we have authoritative assurance from one large refiner of lead that sulphur does not exist in any of their brands of lead even to the fourth decimal place. In view of the perfectly rational explanation of the experiences with dross formation on the basis of accepted causes (metallic impurities) the authors' explanation of the effect of the sodium is not very plausible.

It is noted that they found the Hill standpipe method of filling inadequate until combined with the sodium refining of the lead. In view of their comment about the bad drossing characteristics of the lead which they were using and in view of certain fundamental difficulties with the standpipe method, it is readily seen why there should be difficulties with drossing. Oxides formed on the surface of the high-temperature molten lead would rise partly to the surface of the molten lead but other portions of the dross would attach themselves to the sides of the lead cylinder. Oxide would also be found on the inner and outer walls of the pipe, especially if this was kept at a high temperature so that the initial pouring would be at high enough temperature to melt the surface of the previous charge. Altogether, there would be plenty of reason to expect trouble with oxide inclusions in spite of any gain which might have been obtained as a result of the surface melting of the previous charge.

Along with the vacuum process of filling the lead cylinder, we have combined other refinements of operation as described earlier by Mr. Faucett in his discussion and resulting in the filling of the cylinder with dross-free lead under vacuum conditions not conducive to the formation of any additional dross.

Howard S. Phelps (Philadelphia Electric Company, Philadelphia, Pa.): This paper is one of many evidences of the excellent work done by the cable manufacturers in recent years in response to the demands of cable users for improved lead cable sheathing. The technique described is undoubtedly capable of producing sheathing of a quality superior to that generally available a few years ago. However, it does not deal with the entire problem. Accordingly, there is reason to doubt if the results from it really are superior to those of several other improved techniques already in use.

In considering the problem of obtaining satisfactory lead cable sheathing, it must be realized that, except in the use of European continuous-extrusion machines, there are two distinct weld areas that are potential sources of trouble. These are: (1) the

weld between charges, which gives rise to flow lines; and (2) the die weld, or welds, formed as the two streams of lead meet after passing over the bridge of the die block. The paper by Messrs. Reinitz and Wiseman deals exclusively with the former and ignores the latter.

Analyzing the reasons that support the advantages of uniting the successive charges without welds reveals they are equally important in respect to the die welds. That portion of the description of the new technique concerning the uniting of successive charges stresses the importance of melting the surface of the old charge to facilitate its complete union with the new one. The procedure of introducing the lead of the new charge at a higher temperature, and of directing its flow over the entire surface of the preceding charge, undoubtedly helps accomplish this.

However, the new technique makes no provision for improving the union between the two streams of solidifying lead after passing over the bridge of the die block. Accordingly, the die weld probably remains as weak in the new as in the old technique.

It is fair to conclude that even if one of the two sources of trouble is completely removed, the over-all improvement in quality of the product ceases when the charge weld area has been made as strong as the die weld area. Therefore, it would seem that any technique accomplishing this objective is substantially as good as another.

The foregoing observations apply in particular to the relative merits of the Hill standpipe method of filling the press, rather than to the advantages claimed for the chemically stabilized lead. The latter advantages are not readily apparent from the test data reported.

From table I, the tensile strength of both "electro" lead and "electro" lead plus 0.01 per cent lithium is greater for the sodium treated than for the untreated. However, the reverse relation is true for St. Joseph lead and St. Joseph lead plus 2 per cent tin.

Further inconclusiveness appears in the creep data of figure 7 for the strip specimen at 500 pounds per square inch longitudinal stress and figure 8 for the pipe specimen at 500 pounds per square inch hoop stress. In the former case the treated lead has a greater creep rate while in the latter case it expands less.

These inconsistencies seem to indicate that the differences noted in test data may be a function of the type of lead tested or method of making the test, as well as the process of treating the lead. Certainly the published test data do not convincingly establish the superiority of sodium-treated lead.

The strongest apparent case in favor of the sodium-treated lead is the evidence reported about the type of burst. However, comparing this evidence with that of other independent tests, the reported results are still inconclusive.

For several years, the Philadelphia Electric Company has been studying types of burst in lead cable sheathing, as disclosed by stress-to-failure tests. The results have indicated that extreme caution must be used in drawing conclusions from short-time tests.

It has been found that short-time tests at relatively high stresses result in wedge-shaped fractures that develop from gradual necking down of the lead. On the other hand, for long-time tests at much lower stresses, it can be stated generally that when either die welds or flow lines are involved, the sheaths fail by fractures that develop abruptly without necking down; apparently from a separation of the lead crystals at a weld. For tests at either short time and high stress, or long time and reduced stress, the exact type or character of sheath failures appears to depend on such factors as temperature of sample during test, unit stress in the material, and the composition of the lead being tested, in addition to the success of the weld.

These observations have been found true regardless of the technique for recharging the lead press, or method of purifying the lead. It remains to be seen from actual tests under carefully controlled conditions whether or not the characteristics under discussion will have been improved in the case of sodium lead.

W. H. Bassett, Jr., and **C. J. Snyder** (Anaconda Wire and Cable Company, Hastings-on-Hudson, N. Y.): Messrs. Reinitz and Wiseman have presented a very interesting paper describing the developments which they have undertaken in the Okonite laboratories. In evaluating the results presented, it is suggested reference be made to our paper "Occurrence of Irregularities in Lead Cable Sheathing and Their Relation to Failures," published in the *Transactions* of the American Institute of Mining and Metallurgical Engineers, 1933, volume 104, which is not included in the bibliography in the paper. In this paper we described how uniform cable sheath can be produced by good foundry practice. A number of micrographs of cable sheathing were shown similar to the authors' illustrations, figures 3 and 6. We fail to see any appreciable difference in the structure of the cable sheath resulting from Hill standpipe filling, the authors' figure 6, and the structure of cable sheath produced by our good foundry practice, figures 1, 2, and 3 of this discussion.

We have investigated bottom pouring of lead and have found that it is advantageous in the production of satisfactory calcium-lead-alloy cable sheath or other types of alloys which oxidize rapidly. We have likewise investigated the fusing of the remainder of the old charge to the new charge in the lead cylinder. (For details of movement of lead during extrusion cycle see figure 4 of this discussion.) We have found

Figure 1. Structure of section of carefully prepared lead tube 21 feet from start of extrusion cycle

Figure 2. Structure of section of carefully prepared lead tube 28 feet from start of extrusion cycle

that this fusing is not necessary nor essential, nor is the bottom pouring required when producing common or copper-bearing lead cable sheath. Bottom pouring of castings is an old and useful foundry practice, but cannot be used universally. We have found that there are some grades of lead which cannot be handled by the bottom-pouring method as this practice produces at one location in each extrusion cycle a structural condition in the lead sheath which results in abnormally low tensile strength.

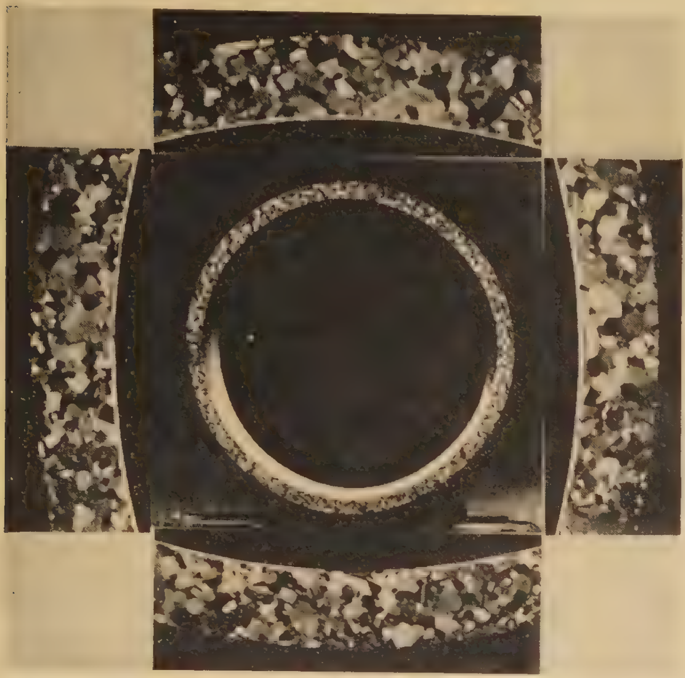

Figure 3. Structure of section of carefully prepared lead tube 77 feet from start of extrusion cycle

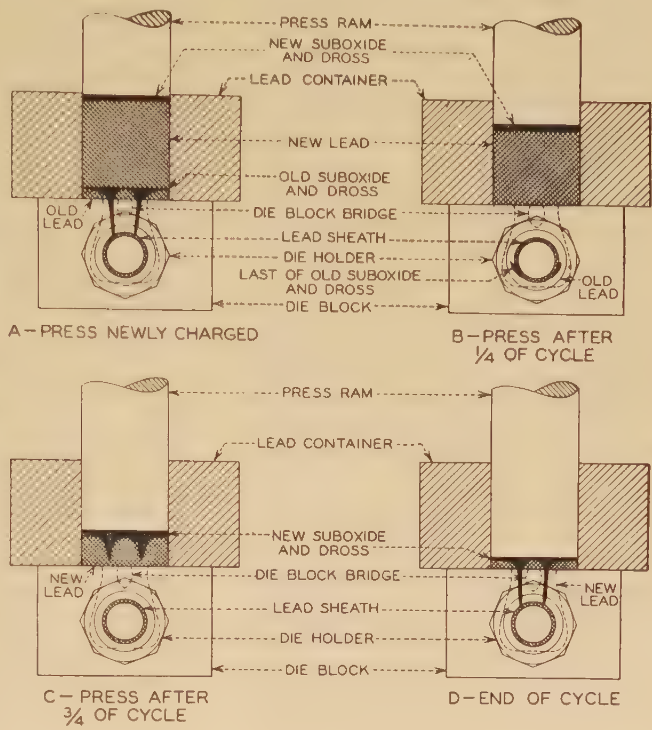

Figure 4. Probable movement of lead oxide and dross as indicated by following sections from extrusion cycle

The quality of a product can be judged only by the results of tests on the finished material which naturally must be free from weak spots. If, as the authors point out, the two charges do not weld together under the heat, pressure, movement of the lead through the cylinder, and the subsequent hot working in the die block, then laminated and blistered sheath would be produced. With the proper technique at the lead press, optimum results are obtained. The term "good foundry practice" as used by the writers refers to the selection of the lead, the melting conditions, the control of the pouring temperature of the lead, bottom pouring, if required, the skimming or cropping operation, the pressure on the lead during the cooling cycle, and the speed and temperature used during the extrusion cycle. We also see that the lead is not contaminated with oil or grease, air or moisture, and, in other words, that all conditions are correct for the casting of a sound billet in the cylinder so that homogeneous lead sheath is produced.

We are particularly interested in the authors' results of internal pressure tests on full-charge lengths of pipe extruded under normal production conditions. In these tests the sample is subjected to 90 pounds per square inch (805 pounds per square inch hoop stress) for ten days, then the pressure is raised ten pounds per square inch every five days until failure occurs. They state that many failures occurred in less than ten days when testing samples produced by their former extrusion practice.

We have made many full-charge bursting tests in the Anaconda laboratories. It has been our experience that all samples break with a knife edge fracture when tested above 100 pounds (1,000 pounds per square inch hoop stress) gauge pressure unless a definitely defective sample was used. We would therefore like to ask the authors what results they would have obtained if they had allowed the tests on their full-charge tests to continue at the original 90 pounds gauge pressure.

In our laboratories, where 2.75-inch outside diameter by 0.133-inch thick full-charge lengths have been tested at normal room temperature (65 to 85 degrees Fahrenheit) under a load of 85 pounds gauge pressure (850 pounds per square inch hoop stress), we have never experienced failures in less than 60 days. It is not unusual to require 90 days in order to reach a failure on a reel of ordinary copper-bearing lead.

We feel that the full-charge bursting tests should be carried to destruction at one pressure, because of the normal characteristic difference in appearance of lead failures at 90 pounds and 130 pounds per square inch pressure (900–1,300 pounds per square inch hoop stress). We have made tests where the pressure was increased in steps and have always obtained knife-edge fractures. It is possible therefore that the authors' test method may give misleading results.

The *Journal* of the Institute of Metals shows that sodium has been used in treating lead for nearly 20 years. In 1920 Thieme[1] reported the hardening of lead by the addition of sodium. In the same year Jones[2] reported good corrosion resistance in a chemical plant by the addition of sodium to lead. He attributes the good effect of sodium to the removal of oxide. Calingeart and Boesch[3] in 1923 report a correction to the lead sodium equilibrium diagrams published by Mathewson[4,5] in 1905 and 1906. A recent patent[6] issued to Magill of Du Pont covers the addition of sodium to lead in order to produce an alloy which is more rapidly corroded than pure lead. The application of this alloy is in the manufacture of white lead or any other operation where the lead is to be dissolved by some corroding agent.

In our early studies of the production of lead cable sheath, we recognized that certain brands of lead made more dross on remelting than others. This subject was discussed with the Anaconda refinery, and, in 1932, they developed a special grade of lead which gave a bright surface on remelting. The refining experts report that the importance of sodium is in the removal of impurities from the lead. On remelting lead which has a relatively low antimony content, we have found that a mirror surface can be obtained. For example the difference in behavior of lead pigs *A* and *B* illustrated below can be readily noted:

	Per Cent				
Pigs Marked	Lead	Copper	Bismuth	Antimony	Silver
A	99.850	0.067	0.072	0.0096	0.0013
B	99.870	0.061	0.065	0.0007	0.0029

In working with calcium lead in 1935, we found that the dross-forming elements were

removed from the lead and that on remelting the lead surface remained bright in the same manner as reported by the authors with respect to sodium.

References

1. Hardening Effects of Various Elements Upon Lead, C. O. Thieme. *Industrial and Engineering Chemistry*, volume 12, 1920, page 446.

2. J. W. Jones, *Journal* of the Society of Chemical Industries, volume 39, 1920, page 221.

3. Calingeart and Boesch, *Journal* of the American Chemical Society, volume 45, 1923, page 1901.

4. Mathewson, *Z. anorg. Chem.*, volume 46, 1905, page 94.

5. Mathewson, *Z. anorg. Chem.*, volume 50, 1906, page 171.

6. United States Patent 2,106,555 issued to Paal LaFrone Magill and assigned to the Du Pont Company.

B. B. Reinitz and R. J. Wiseman: Reviewing the comments made by several of those discussing the paper, we note a similarity in points raised as well as lack of understanding of what the paper actually describes. Therefore, the following restatement of several facts may help to correct a misinterpretation of the paper and thus eliminate the necessity of making duplicate replies to comments. We do not consider the addition of sodium in the quantities used as a refining or purification process or alloying of the lead. In the first place, the amount used is very small and the quantity remaining in the lead for sheathing is so small that it has no influence on the physical properties of the original lead. This has been proved by tests. As the amount of sodium remaining in the lead is of the order of 0.001 per cent to 0.002 per cent and far less than that of other foreign metals which the lead may contain in the brands of commercial lead used at present for cable sheathing, it is hard for us to understand why it is thought we are alloying when, as we state above, our process does not change to any extent the physical properties of the lead. In other words, we do not contaminate the lead, we do not endeavor to make the lead harder, nor do we increase its vulnerability to corrosion. As the cable specifications allow a total of 0.15 per cent of metallic impurities in the lead for sheathing purposes, and we normally are well within this value, the process does not cause the chemical composition to be materially changed from a commercial viewpoint. We do not try to improve the chemical composition, that is, by the addition of sodium, no attempt is made to reduce the quantity of other metals present in lead as some refiners have done in the past when they added as high as three to seven per cent of sodium and using entirely different processing methods. We purposely use only sufficient sodium to cause the oxides and sulphides which are already present, or the oxides formed during heating, to decompose or to be thrown out of solution. We call these the deleterious impurities, as distinguished from the metallic impurities. Our treatment is quite limited in this respect as otherwise we would get into the same difficulties of corrosion that others have experienced where larger quantities of sodium are used. It was the discovery that it is the extremely small amount of sodium which prevents oxidation and removes the oxides and sulphides which makes this process of value. Metallurgically, purification and refining consists in reducing the amount of metallic impurities. We do not consider our process as such, but rather look upon it as a cleansing and stabilization, what might be called a scavenging of the nonmetallic impurities which, heretofore, have not been properly recognized as one of the major causes of the defects in lead sheathing.

Using this improved lead in combination with the method described for uniting charges, a better lead sheath is obtained. Our tests and customers inspection reports extending over a period of years have all indicated this. We believe, and, as stated in the paper, "that this method or some other method which brings about the same results, namely elimination of flow lines and laminations, is necessary," if we are to hope for lead sheaths which will give a longer life than in the past. Some of the methods used by other manufacturers only accomplish certain specific ends instead of everything that is desired. The vacuum press and hydrogen-flame treatment are notable in this respect. With the treating of the lead described in the paper not only is oxidation of the lead both in the melting pot and during the filling of the cylinder prevented but also, by the use of the standpipe, we actually cause the successive charges to be 100 per cent united. This has been proved by many tests over several years. In these tests, the full charge in the lead block and cylinder is removed as a solid block, cut in half, planed, and etched with the lead consistently giving cross sections such as shown in figure 5.

Comments have been made that perhaps we have been using inferior brands of lead and that something must be done about it. Such is not the case. Like other manufacturers we purchase the standard commercial brands of lead required to meet ASTM specifications. For the purpose of this paper, in order to emphasize what can be accomplished by such treating of the lead, we took (1) St. Joseph lead which everyone acknowledges is one of the highest grades of commercial lead, and which drosses to the same degree as other brands, and (2) electrolytic lead which is of a higher commercial metallic purity but oxidizes more readily. This shows that this treatment greatly improves all kinds of commercial lead from the standpoint of oxidation and at the same time does not adversely upset the other properties of the lead.

It has been suggested that a more elaborate list of references be given. As with most papers, more could be given if one wishes to take the space for them. We included those which we felt would cover the subject matter sufficiently for those who cared to go into it further. We wish to acknowledge the paper by Mr. Bassett in the *Transactions* of the AIME which reviews very well the lead problems which have confronted cable manufacturers in recent years.

We agree with Mr. Halperin that imperfect welds and nonmetallic inclusions usually constitute the initial set of causes for sheath failures. We remove the nonmetallic inclusions by the stabilization of the lead and eliminate the imperfect weld by our method of filling. What is at times considered as a defective die weld might be a poor charge weld where the laminations resulting from the nonunion of charges abutt the die weld. At times the charge weld is only about $^1/_{64}$-inch from the die weld and cannot be seen except by magnification after etching. In view of the above it is many times mistaken for a die weld.

It is recognized that more or less sound cable sheaths are extruded now by some cable manufacturers. However, it is the consistency of good foundry practice throughout the cable length that is essential, and not at the ends or scattered along the reel lengths. By the method described in the paper we are able to control, at all times, both the condition of the lead and the elimination of flow lines and laminations.

We are not able to agree with Mr. Bassett that the fusing of the successive charges is not necessary nor with his statement that some grades of lead cannot be handled by this method. Our studies have clearly shown complete fusing is essential if it is desired to eliminate flow lines. Careful examination of figure 1 which Mr. Bassett submits will disclose a flow line in the so-called critical region where metal from the vicinity of the contact of the two charges in the cylinder extrudes as pipe. We have used different grades of lead and tests have not shown low tensile strength.

In a manufacturer's laboratory it is necessary to obtain results in a reasonably short time, though long enough to be able to produce results comparable to service conditions. We believe this is accomplished by the pressure-time step test which we make on full-charge lengths of empty pipe, as, early in our studies, we obtained small slits in the pipe such as occur in service. The time taken for test is empirical and as the same method is used all the time we are enabled to compare the results. Answering Mr. Bassett on what would have been obtained if we had allowed our tests to continue at the original 90 pounds gauge pressure, we would expect it to continue for months before rupturing. Leaving samples under test so long does not help in completing a research in a reasonable length of time, nor is it an aid to learning whether improvements are being made. After a test has been completed and microscopic examination of the lead in the vicinity of the rupture has been made one can tell whether there were any defects in the pipe to have caused an earlier rupture than would otherwise occur.

Our review of the literature on the use of sodium in the treatment of lead shows that it has been used for about 50 years. However, the amount, form, and method have been distinctly different from the procedure described in the paper. Moreover, purification of the lead from foreign metals was attempted rather than the cleansing or stabilization from nonmetallic inclusions. Refining experts were only interested in removing metallic and not nonmetallic impurities, and, therefore, failed to appreciate how small quantities of sodium could remove oxides and sulphides, equally as objectionable as metallic impurities.

We do not agree with Doctor Simmons regarding the effect of metallic impurities on dross formation. The amount of sodium that we use does not eliminate metallic contamination nor is sodium hydroxide formed to contribute a colorless slag.

Where cable manufacturers may be criticized, is for their failure in the past to recognize that all brands of lead will dross. It seems to have been accepted as a natural

evil of little importance (the drossing is hastened in the melting pot and according to good foundry practice all manufacturers periodically cleaned out the red oxide) instead of finding means for the removal of this dross or oxides contained in the lead, as received, and seeing that further oxidation was prevented. Our process has accomplished this and it seems evident that no other process does the same. There have been improvements by some manufacturers in the lead-press operation, but not enough, and with no such treatment of the lead as the paper discusses.

The storing of lead outdoors and surface oxidation is not the whole story. Allow remelted lead to stand around and it will soon lose its luster, but this is merely a surface condition as there are still oxides dispersed through the lead.

The table herewith may help to show that sodium in the amounts that we use does not throw out other foreign metals from lead, that is, it is not a purification process. A quantity of antimony (0.07 per cent) was added to lead which was then heated to 850 and 1,200 degrees Fahrenheit, held at these temperatures for 30 minutes, and then checked for antimony content. The experiment was repeated for lead which had been treated with 0.02 per cent sodium. The results are as shown in Table III.

The time of treatment in the factory is much less than 30 minutes. It is the high temperature of 1,200 degrees Fahrenheit and not the sodium that reduces the antimony content.

We have relied too much on the statements of metallurgists on what is good or bad in lead. They confine themselves to the metallic phase of lead rather than realizing that the nonmetallic phase of lead may also be important. This was clearly shown by a refiner when he was told that we found sulphides in his lead. He first disagreed but after checking a sample confirmed our findings. Upon request that the sulphides be eliminated we were informed that commercially it would be too costly. That is, the refinement would not be justifiable in view of the small quantity of lead used for cable sheathing purposes as compared to general trade consumption. This seemed a logical reason and we thereupon set up our premelting pot to eliminate the oxides and sulphides.

We do not say that the Hill standpipe method of filling is inadequate unless its use is combined with the sodium treatment of lead. Rather, the paper shows there is a distinct improvement in the mechanical properties of a cable sheath through use of the standpipe but that it is desirable to go further by eliminating the oxides and sulphides in the lead, thus accomplishing a thorough job instead of a partial one.

We are in accord with Mr. Faucett that to overcome troubles it is necessary to eliminate the source of the trouble. The nonunion or nonfusing of successive charges is the cause of flow lines and laminations. These are eliminated by the use of the Hill standpipe method of filling the cylinder. The presence of oxides and sulphides in the lead are the source of weakness in crystal structure and our treatment of the lead overcomes this trouble. We think Mr. Faucett did not consider that the amount of sodium retained in the lead is far less than the amount of bismuth, antimony, arsenic, and copper which may be present and therefore the resulting lead composition is about the same as before it was treated.

There was no need of mentioning ram lubrication in the paper. We have not experienced the difficulties some others have had with it, even before the development of our new processes.

Chilling of the lead ram and cylinder walls is not of importance nor does chilling of the surface of the previous charge cause oxidation. Heat is the cause of oxidation, particularly if the lead is in a molten state. Our treatment prevents the latter from occurring while the lead is being poured into the cylinder and that is why it is so effective. Fundamentally, it is desired to have the successive charges to unite, heating of the ram or cylinder walls will not accomplish it. The surface of the residual charge must be melted and what better and easier way to do this than with the new charge so that the two charges are united as one. We question that the vacuum-press method unites charges and would be interested in seeing slugs similar to those shown in figure 5, to prove that it does.

As we view it, if an alloy of lead is formed by the addition of sodium, we should expect some physical or chemical change in the lead. It has been shown that we do not change the physical properties and, as far as we can tell, it is not in chemical combination with lead. The composition of the resulting mixture of the lead is still well within that expected in commercial lead, which may contain as much as 0.06 per cent copper, yet we do not consider this lead as an alloy in the commercial sense.

The amount of physical data which has been given on stabilized lead in the paper represents only a part of the tests already made and we consider these data sufficient to show that the process does not adversely change the properties of the lead. Regarding corrosion, we are fully cognizant that there are many factors which influence corrosion. It is also shown that the sodium treatment of lead does not intensify the corrosion rate of lead in solutions which are representative of those that occur in service. If unduly large quantities of sodium were used in lead, corrosion would then be very severe. The amount of sodium in the samples used for corrosion tests was the maximum which will be present in actual commercial production. We have had samples of pipe under study similar to field conditions for about three years and so far there has not been a single case where trouble occurred.

Referring to Mr. Faucett's comments on the type of deposit on the lead when subjected to steam and the solubility of the corrosion film: it is our understanding that where severe corrosion is encountered, neither a soluble or insoluble, adherent or nonadherent film will protect a lead sheath. It is necessary to use protective coverings such as rubber or synthetic plastics. At the same time, where the corrosion films are of the nonsoluble, adherent type, they are generally embedded not as uniform films but as segregated incrustations, and thus pronounced pitting takes place which hastens failure.

We agree with Mr. Faucett that the data on physical properties are within the degree of experimental error and that is why it is claimed that the properties of the treated lead are not changed. We are not trying, for example, to obtain higher tensile strength but are cleansing the lead before it is used for sheathing in order that the resulting pipe will be more uniform in its characteristics throughout its entire length than is possible with lead not so treated. We are able to control very easily the treatment of the lead and none of the difficulties anticipated by Mr. Faucett has been experienced.

We do not agree with Mr. Faucett that the microstructure of extruded pipe shown in figure 3 is not representative of present day practice as a whole. Some cable manufacturers have improved their previous practice but we have been able to examine sheaths occasionally and have found flow lines even in pipe from the vacuum press.

We wish to correct Mr. Faucett's statement that we have not investigated the vacuum press. We do not use the vacuum press but we have thoroughly investigated it and studied it in operation. We decided that it did not accomplish what we wanted, namely, uniting of the charges. The ram and cylinder operation is complicated and the melting pot, although good, does not remove sulphides and other deleterious impurities, such as allotropes of lead formed in the initial stages of oxidation. These have specific gravities close to that of lead and are dispersed through the lead.

We wish that the alkalies used in standard refining methods were effective in removing sulphur as that would save the expense of using a separate treating operation.

It is agreed that oxygen is not present in significant quantities and the paper does not make this statement. If oxygen were present, it would immediately react with molten lead to form lead oxides. It is pointed out in the paper that, after the treatment of the lead with sodium, there remains about 0.001 per cent sodium in the lead. This prevents further oxidation while the lead is in the melting pot and while being poured into the cylinder, even though it is exposed to the air.

No difficulty has been experienced in etching or taking photographs of our stabilized lead with the same etching solutions as used for nontreated lead. Rather than tarnishing more readily, the surface of the treated lead remains brighter for a much longer time.

As before stated, we use the commercial brands of lead, and, like others, did not ap-

Table III

Per Cent					
Antimony Added	Sodium Added	Antimony Retained	Sodium Retained	Heated to Deg F	Duration of Heating (Minutes)
0.07		0.07		850	30
0.07		0.035		1,200	30
0.07	0.02	0.07	0.001	850	30
0.07	0.02	0.035		1,200	30

preciate that the oxides and sulphides present were in sufficient quantities to be objectionable although actually of small magnitude.

Through our method of filling no difficulty is encountered in obtaining a completely fused area. A permanent bond, clear to the edge of the cylinder and for about four to six inches into the old charge, results from this procedure, as is shown in figure 5, and by the numerous etched slugs on exhibition in our laboratory.

References 11, 12, and 13 cited in the paper clearly show that certain oxides are to some extent soluble in molten lead. Naturally, it is obvious that it is only on solidification that segregation along boundary lines will take place.

It is well known that the presence of metallic impurities in lead will decrease the tendency to form dross. For instance, lead containing small quantities of copper, tin, or antimony will definitely form less dross for a given time and temperature than lead free from metallic impurities as reported by G. O. Hiers. Thus, if we are to accept Mr. Zickrick's statement that the lead used by D. M. Smith contained more metallic impurities than in use at present by the cable manufacturers, then the tendency to dross, especially under reduced pressure, should have been eliminated at least after the first heat and vacuum treatment.

It is true that the purer the lead the lower will be the tensile properties and the larger will be the grain size and the lower the resistance to fatigue. However, by our technique of sodium treatment, metallic impurities are not removed. The process is a stabilizing one and not a metallurgical refining process. Therefore, the tensile strength of sodium-treated lead is the same as for untreated lead while the resistance to creep is somewhat greater owing to the more uniform and better bonding of the crystals.

The tensile-strength figures given for treated and untreated lead in table I are all very similar and within five per cent, except for the electro plus 0.01 per cent lithium. Tensile tests on strips cut from lead pipes cannot be expected to check any closer than 5 per cent.

The treated electro plus 0.01 per cent lithium lead has a higher tensile strength than the untreated, probably due to the formation of a binary alloy of sodium and lithium.

Regarding figure 7, it is well known that when the creep rate of two leads is compared, the stress at which it is tested must be taken into account. Thus the creep rate of noncopper-bearing lead is much greater than that of copper-bearing lead when tested at 850 pounds per square inch, but the creep rates are equal at some lower stress.

The 500-pound-per-square-inch creep tests of figure 7 and figure 8 are not strictly comparable, one being made on strip and the other on pipe. In the pipe tests the lead is stressed in at least two directions, but in only one direction on the strip tests. The simple pipe formula was used for calculating hoop stress and not the Philadelphia Electric Company formula.

We agree with Mr. Phelps that different results may be obtained when making long-time and short-time tests. We do not consider our tests as short-time tests because, even with the pressure steps used, they have extended over periods of a month or more.

Instruments and Methods of Measuring Radio Noise

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Synopsis: This paper embodies the relevant agreed recommendations of the Joint Co-ordination Committee on Radio Reception of EEI, NEMA, and RMA, as to the nature, essential characteristics, and performance of an instrument for the measurement of radio-noise voltages. It further gives detailed descriptions of the recommended practices for measuring radio noise directly from low- and high-voltage apparatus, for making noise measurements along overhead lines, for determining broadcast field-strength levels, and methods of collecting data for the establishment of radio-noise standards.

RADIO-NOISE effects are produced by extraneous electrical fields associated with transient conditions in an electric circuit. In order that apparatus producing these effects can be treated and described in precise terms and the most satisfactory method of radio-noise suppression employed in a given case, it is necessary that there be some means of measuring the radio-noise voltages that are significant in relation to radio reception. It is also desirable that there shall be a national understanding and agreement as to the method of measurement.

The noise voltage produced by electrical apparatus on a given system depends upon the high-frequency voltage generated, the internal impedance of the apparatus, and the character and impedance of the load. This voltage is propagated by conduction, induction, radiation, or a combination of these. All metallic materials, whether used normally for electrical systems or for other purposes, may conduct high-frequency energy.

The radio-noise effect of electrical apparatus on a receiver antenna is influenced by most of the above factors. No definite method has been developed that will permit the calculation of voltage on a receiver antenna when the noise voltage produced by electrical apparatus is known.

Through the co-operative efforts of the Edison Electric Institute, National Electrical Manufacturers Association, and Radio Manufacturers Association, the measurement of radio noise has been placed on an engineering basis. In 1932 this committee adopted specifications for a radio-noise meter and methods of measurement. These were published in NELA Publication No. 32 in 1933. These specifications were revised and published in EEI Publication *C*9, NEMA Publication 102, and RMA Engineering Bulletin No. 13 in 1935. Due to the advances in the radio art and the increased use of the radio-frequency spectrum, it has been necessary to extend and bring up to date these specifications. All the field data in this paper were taken with a meter built according to the old specifications. However, similar data taken with an instrument according to the new specifications would not be sufficiently different to change the interpretation of the results.

The development of these specifications has resulted in the application of engineering principles to the reduction of radio noise produced by certain types of electrical apparatus. The continuation of this work shows promise of producing more beneficial results in the future.

Radio-Noise Meters

A meter for measuring radio noise should give results which are comparable with the effect of the noise as heard in the loudspeaker of a radio receiver, and at the same time should be accurate and rapid in operation.

Radio noise from different types of apparatus differs in character; some types of noise have high amplitude but are of short duration, whereas others are more nearly sinusoidal in form. Furthermore, the characteristics of the radio receiver upon which the noise impinges will have an effect on the noise characteristics, so that the wave shape of the noise pulse at the output of the receiver may

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differ materially from that at the input.

A noise meter designed to measure the characteristics of the noise pulse as it exists at the input to a radio receiver would be a complex and cumbersome piece of equipment because it would be required to measure noise potentials of the order of microvolts and would have to be capable of amplifying all types of pulse shapes without distortion. Such a device would not be suitable for field measurements and furthermore the results would require correlation with observations of the interfering propensities of the many types of noise.

The most practical type of noise meter is one which is essentially similar to a radio receiver, with indicating means in the output. Such a device may be made convenient to operate, portable, and reliable. The indications of noise intensity for various types of noise on this type of noise meter depend upon the design constants chosen, but it is preferable to have a simple indication such as this type of noise meter provides and then to classify types of noise-making apparatus if necessary, rather than to use a complex noise meter which does not alter the noise pulse, as in the latter case classification of noise types is replaced by correlation of pulse shapes.

Indicating Means

There are three general types of output indicators which may be used:

1. Oscilloscopes
2. Wave-form analyzers
3. Indicating meters

Oscilloscopes and wave-form analyzers are useful for theoretical investigation of noise, but do not provide ready numerical means of expressing results, and are more difficult to use than an indicating meter. Indicating meters are convenient and reliable so are to be preferred for general use.

Frequency Range

The noise meter should cover the entire radio spectrum of interest for reception, which is from approximately 150 kilocycles to at least 100 megacycles. However, the design problems for frequencies above 20 megacycles differ materially from those for frequencies below that value so that it is more practical to design two separate instruments, one for frequencies below 20 megacycles and one for frequencies above 20 megacycles. This discussion will be confined primarily to the meter for frequencies of 150 to 350 kilocycles and 540 to 20,000 kilocycles. The wide frequency range dictates the use of the superheterodyne circuit, and because the intermediate frequency thereof will probably be the RMA standard value of 455 kilocycles, there will be a range on either side of this frequency which will not be covered, namely 350 to 540 kilocycles.

Detectors and Indicating Meters

Since the noise is transmitted through the instrument at radio frequencies, detection is necessary before applying the resultant audio-frequency pulse to the indicating meter. The indicating meter may be arranged to read root-mean-square, average, or peak value of the wave. It is generally recognized that on noise pulses of short duration, meters reading average or root-mean-square do not indicate values as high as those disclosed by listening tests. A peak or quasi-peak indicating device has been found to give meter readings more nearly proportional to the auditory interference experienced. Since a peak-reading meter is desired, the meter may be in the detector circuit, thereby eliminating audio amplification. The use of a meter in the detector circuit has the further advantage that calibration of the device can be made by application of an unmodulated carrier-frequency voltage, thus eliminating the necessity of modulation thereon, and eliminating the necessity of determining the modulation factor.

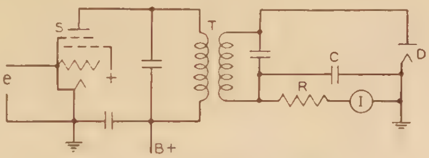


Figure 1. Detector circuit

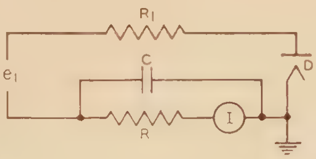


Figure 2. Equivalent detector circuit

A detector for noise measurement should meet special requirements, but with due regard for practical design limitations. A typical diode detector, which is the most satisfactory and reliable type detector, is shown in figure 1. The radio-frequency voltage, e, noise or signal voltage as the case may be, is applied by preceding amplifier circuits to the input of the final intermediate-frequency amplifier tube S. Tube S in turn impresses the voltage on diode D through the intermediate-frequency transformer T. In the diode circuit are a resistance R, a capacitor C, and the current-indicating meter I. Tube S and transformer T can be replaced by an equivalent voltage e_1 and resistance R_1 as shown in figure 2. Capacitor C is charged by e_1, through R_1 and discharges through R. The time constant on charge is then R_1C and on discharge RC.

If voltage e_1 is a suddenly applied potential, capacitor C will charge to 63 per cent $(1-1/\epsilon)$ of e_1 in time R_1C. On discharge the voltage of C will drop to 37 per cent $(1/\epsilon)$ of its initial voltage in time RC. Now if the discharge time constant RC is long in comparison with the charge time constant R_1C, the voltage of C will build up to very nearly the peak value of the applied voltage. In considering the mechanism of build-up of voltage to the peak value, it should be borne in mind that noise voltage consists of a series of impulses, the measured voltage reaching essentially the peak value after the first few impulses. In the very rare case of noise consisting of a single pulse, or pulses with a repetition time longer than the discharge time constant of the metering circuit, a value considerably less than the peak would be indicated. However, experience would tend to show that the disturbing effect of such noises on the listener is less than would be indicated by their peak amplitude.

In determining the time constants of the metering circuit, consideration must be given to meter characteristics, noise characteristics, and to circuit design limitations. An indicating meter which is too rapid in action is expensive and is difficult to read, whereas a meter with too long a time constant makes circuit design difficult. A meter with a time constant of 200 to 400 milliseconds is suitable, the time constant of the meter for this use being considered as the time required for the meter to deflect from zero to an equilibrium position upon the application of a steady current equal to about two-thirds full-scale value. This corresponds to a meter with a natural period of 0.5 to 0.7 second with a damping factor of 10 to 100 determined according to American Standards Association standard methods.

It is desirable that the time constant of the noise meter be determined by the circuit values rather than by indicating-meter constants, because the former are more readily determined and may be held more closely. By making the circuit charge time short and discharge time long in comparison with the indicating-meter time constant, this may be accomplished.

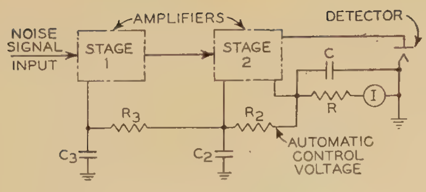


Figure 3. Logarithmic amplifier

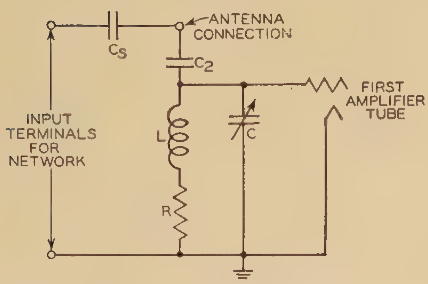


Figure 4. Input circuit

It is difficult to secure an equivalent resistance on charge (R_1 of figure 2) of less than 20,000 to 30,000 ohms with receiving-type vacuum tubes, whereas fixed resistors for discharge (R of figure 2) become difficult to determine accurately and are not stable in value above approximately 5 megohms. This, therefore, in conjunction with the indicating-meter constants determines the permissible range of values for C and for charge and discharge time constants. It should also be borne in mind that the peak voltage is given by IR so that for any value of voltage, the lower we make R, the greater I will become, thus permitting use of a less sensitive indicating meter. In some cases where it is desirable to use a relatively insensitive meter and a high value of R, a d-c amplifier may be used. From the above considerations, a charge time constant of the order of 10 milliseconds and a discharge time constant of the order of 600 milliseconds are indicated.

The following tabulation shows several possible combinations of circuit values which result in these time constants for charge and discharge.

R (Megohms)	C (Microfarads)	R_1 (Ohms)
5	0.12	83,000
4	0.15	67,000
3	0.2	50,000
2	0.3	33,000
1	0.6	17,000

If it is desired to measure the signal intensity of a broadcast-station carrier or to use the audio-frequency noise output for listening or other type of indication, the time constant RC should be of the order of 0.1 millisecond, which may be done by appropriate reduction in the value of C when such measurements are required.

Selectivity

Steep-wave-front disturbances involve a broad band of frequencies for their transmission and when transmitted through a selective amplifier undergo a change in shape. The energy content of a high amplitude pulse of short duration is unchanged by a selective amplifier, but its maximum amplitude is decreased and its duration correspondingly increased. Since this shape alteration of sharp pulses takes place in radio receivers in proportion to their selectivity, in order to correlate noise-meter indications with radio reception, it is desirable to have comparable selectivity. The over-all pass band of radio receivers, from antenna to loudspeaker, varies widely, from about 1,500 cycles in the lowest-priced receivers to 6,000 or 8,000 cycles in the case of receivers of high fidelity. Since good-quality receivers merit additional consideration, the noise meter should have somewhat greater pass band than that of the average receiver. The high-frequency end of the pass band is of prime interest, frequencies lower than 60 cycles seldom being of interest in noise studies. The noise meter should then transmit frequencies of 4,000 to 5,000 cycles, which means the selective circuits should have a band width twice as great because of double-side-band considerations.

Sensitivity

While it is desirable to have signal intensities of five to ten millivolts per meter from broadcasting stations for good reception, there are many localities where no signal over 500 microvolts per meter is available. A signal-to-noise ratio of 30 decibels for average program to average noise is generally conceded to constitute a minimum ratio for acceptable reception so that the noise meter must be capable of measuring noise voltages of the order of ten microvolts. It is seldom that noise voltages of more than 100 millivolts are of interest, which determines the upper limit of noise-meter calibration. However, such voltages should not undergo any limiting action by the noise meter, nor should such voltages cause generation of spurious responses, so the amplifiers of the noise meter should be capable of handling peak values up to about ten volts input.

Meter Scales

A scale on the indicating meter which is logarithmic in character has several advantages over a linear scale. In the first place it fulfills the psychological conditions of Weber's law and in addition makes the use of fewer attenuator taps possible, with resultant increase in simplicity of construction and use.

The logarithmic characteristic is best secured by electrical means. The deflection law of the meter itself is linear, the angular deflection of the pointer being proportional to the current through the meter.

The automatic-volume-control system as used on radio receivers provides a ready means of obtaining such a characteristic. By the use of remote-cutoff vacuum tubes in the noise-meter amplifier stages, a sufficient amount of control can be applied to each stage to obtain a useful input range of about 40 decibels on each meter scale range without amplifier overload or distortion.

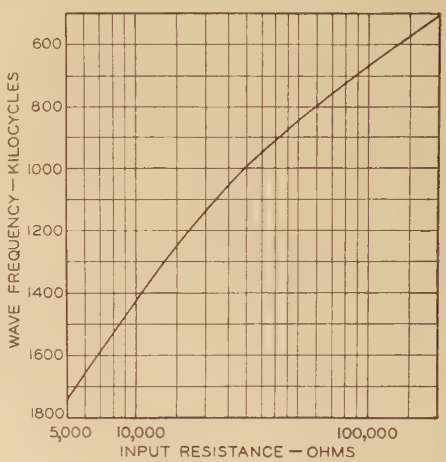


Figure 5. Noise-meter input resistance with circuit of figure 4

In figure 3 is shown the method of obtaining logarithmic indication. The direct current developed by the detector is filtered by R_2C_2 and R_3C_3 to eliminate any intermediate-frequency or noise component and is then applied to bias the amplifier stages. The time constant of the filter should be of the order of 200 milliseconds so that it will not influence the meter indication, the time constant for noise measurement being that of the detector circuit only.

The meter scale is calibrated logarithmically in microvolts or linearly in decibels above one microvolt and the value of noise input in microvolts is thus read directly on the indicating meter.

The meter scale is useful over a ratio of inputs of about 100 to 1 by virtue of the logarithmic system used, but in order to cover the entire desired range of 10 to 100,000 microvolts, multipliers of 10

and 100 should be used. These multipliers are in the form of attenuators for the noise input, and in order that none of the tubes be overloaded, must precede the first tube. The attenuator may be of the resistance type, or may be of the capacitance or mutual inductance type, any one of which can be made to have the desired attenuation independent of frequency.

Input Circuits

The input circuits should be suitable for use either with a vertical-rod antenna for measuring noise or signal field intensities or as a voltmeter. In either case the impedance of the input system should be high, so that the voltage existing on the antenna or across a standard coupling network will not be affected by connection of the noise meter. One type of input circuit which fulfills these requirements is shown in figure 4.

The antenna should be a relatively short vertical rod with an effective height of one-half to one meter which means a physical height of approximately twice that value. Such an antenna has an inherent capacitance of 10 to 20 micromicrofarads, and C_s should have the same capacitance so that the input circuit will be tuned correctly when the meter is used either with the antenna connection or as a voltmeter.

The impedance of this type input system is a pure resistance when tuned for maximum response as the *LRC* circuit under such condition becomes an equivalent resistance and inductance in series, the value of the inductive reactance being equal to the capacitive reactance of C_s and C_2 in series. In order to secure a suitable high impedance, a small capacitance C_2 is placed in series with the circuit. The capacitance of C_s and C_2 in series should be of the order of three micromicrofarads. If we assume this to be three micromicrofarads and L to be 166 microhenries, and the power factor of L to be one per cent, at broadcast frequencies, the equivalent resistance of the input circuit as a function of frequency will be as shown in figure 5.

Calibration Source

The noise meter should be battery operated for field use, which means that the gain will change with battery usage as well as due to aging of tubes and effects of atmospheric humidity. In order to make the instrument readings accurate, the gain must be standardized each time the instrument is used. The gain standardization requires the incorporation of a self-contained calibrating source. The primary calibration should be performed by means of a standard signal generator but a comparison standard must also be included in the noise meter itself.

There are three possible types of calibration sources which might be used, an internal radio-frequency oscillator with a meter to indicate its output, the inherent thermal agitation noise voltage of the noise-meter input circuit, or the shot noise from a saturated diode. The latter two are simple to incorporate and depend only upon constancy of resistance of the input circuit. For an input circuit resistance of 10,000 ohms and a band width of 6,000 cycles, the thermal agitation voltage is 1 microvolt at a temperature of 20 degrees centigrade, whereas the shot noise for a current of one milliampere is 14 microvolts, under the same conditions, so is easier to apply.

The shot noise voltage is given by

$$V_s^2=31.8\times10^{-20}iR^2F$$

at a temperature of 20 degrees centigrade where

V_s is shot noise voltage
i is current in amperes
R is input circuit parallel equivalent resistance in ohms
F is frequency pass band in cycles

The circuit of figure 6 may be used for the calibration source. *LC* is the input tuned circuit and R is a resistance shunted across this circuit during calibration so that the total circuit resistance will be more uniform with frequency. B is a battery of sufficient voltage so that the diode draws saturation current. R_1 is a resistor which varies the diode filament temperature until the space current as read by meter I reaches the calibration value. Meter I may be the output indicator of the noise meter switched to the position shown in figure 6 for calibrating purposes. The amplifier gain is then adjusted to standard value by variation of screen or initial bias potential.

In the design of such instruments, due consideration must also be given to shielding, image-frequency response, and intermediate-frequency response ratios, so that the noise indicated is due only to that existing at the frequency to which the meter is tuned.

Methods for the Measurement of Radio-Noise-Influence Voltage Produced by Electrical Apparatus

The term "noise-influence voltage" will be used hereafter to describe the radio-noise voltage measured at the terminals of electrical apparatus when connected to a coupling network. This term is used in order to make a definite distinction between this voltage and the radio-noise voltage that may appear at the input terminals of a radio receiver. The noise voltage that appears between the antenna and ground will hereafter be referred to as the "noise voltage."

Noise-Influence Voltage of Low-Voltage Devices

The noise voltages produced by low-voltage electrical apparatus are generally caused by the transmission of high-frequency currents along the wires or conductors connected to the apparatus. These currents are due to the electromotive forces produced by the apparatus at its terminals. As such apparatus is generally grounded or has a substantial capacity to ground, the currents will not be confined to the conductors connected to it but will in addition be propagated via ground. It is, therefore, necessary

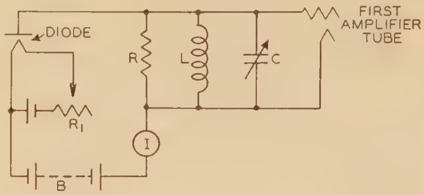


Figure 6. Calibration method

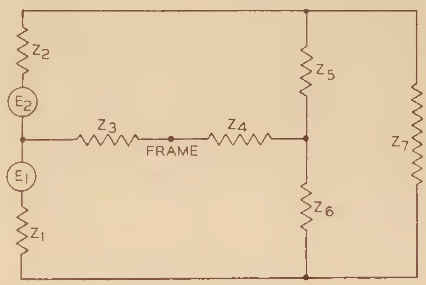


Figure 7. Equivalent circuit showing the various impedances involved when a universal motor is connected to a line

Z_1, Z_2—Impedance of field windings
Z_3—Capacity of field windings and armature to frame
Z_4—Capacity of frame to ground
Z_5, Z_6—Impedance from line to ground
Z_7—Impedance from line to line
E_1, E_2—High-frequency voltage developed at brushes

to consider the disturbing currents as consisting of two components, one corresponding to the electromotive force acting between the various conductors, hereafter referred to as the line-to-line noise-influence voltage (E_L) and the other

corresponding to the electromotive force acting between the ground as one pole and the conductors jointly as the other, this being hereafter referred to as the line-to-ground (E_G) noise-influence voltage.

Effect of Variation in Termination on the Noise-Influence Voltage

The amplitude of the noise-influence voltage produced by electrical apparatus is determined by the external terminating impedance as well as its internal impedance. This may be seen by referring to figure 7 which is a simplified circuit for the various impedances involved when a universal motor is connected to a supply line. It will be noted that the line impedance network is represented as a delta system. In service conditions, the voltage induced upon a receiver antenna is associated with the vector sum of the voltages across Z_5 and Z_6. Consequently, any network that is developed should be so designed that the line-to-ground component will be taken vectorially. This can be accomplished readily by a star network as shown by figure 11.

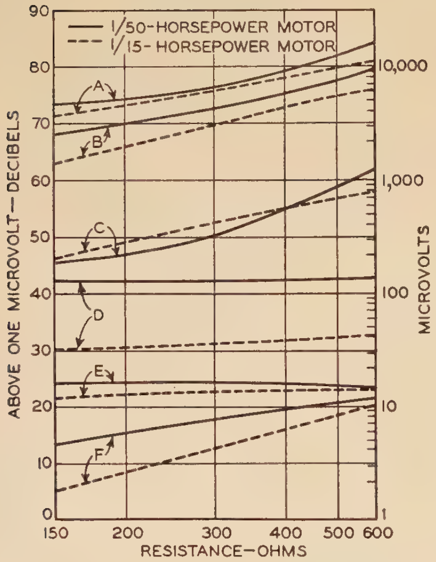


Figure 8. Noise-influence voltage from 1/50- and 1/15-horsepower universal motors with various terminating impedances

A—Line to ground, frame grounded
B—Line to line, frame grounded or ungrounded
C—Line to ground, frame ungrounded
D—Line to line, frame grounded or ungrounded—filtered
E—Line to ground, frame grounded—filtered
F—Line to ground, frame ungrounded—filtered

The noise-influence voltages produced by $^1/_{50}$- and $^1/_{15}$-horsepower motors with terminating impedances of 600–300 and 150 ohms are shown by figure 8. It will be seen that the measured average noise-influence voltages are seven decibels higher with 600 ohms than with 300 ohms and five decibels higher with 300 ohms than 150 ohms in the following conditions:

1. Line-to-line, grounded or ungrounded (not filtered)
2. Line-to-ground, grounded and ungrounded (not filtered)
3. Line-to-ground, ungrounded (filtered)

Where filters are applied to the motors all three impedances give identical line-to-line and line-to-ground (frame grounded) voltages.

Some field tests have indicated that the variation in the impedances of supply lines in homes may vary from 10 to 2,000 ohms with an average around 150 to 300 ohms. Other investigators have measured an average impedance of 80 ohms. The supply-line impedances vary considerably from location to location and are not pure resistances but contain reactive terms. Some of the supply lines that have been measured were resonant in the broadcast band. Lines with impedances that contain reactive terms may increase or decrease the noise voltage from electrical apparatus, depending upon their phase relation with respect to the internal impedance of the apparatus. The impedance of supply lines may vary from day to day. Turning on a lamp may change the line impedance characteristics so as to cause the noise voltage from apparatus to increase or decrease a considerable amount.

Field tests indicate that the impedance of each wire to ground is different, thereby causing a high-frequency unbalanced termination for the apparatus. Laboratory tests have indicated that the minimum noise voltage from electrical apparatus will be obtained when the terminating impedances are balanced with respect to ground. A mathematical analysis of figure 7 will also show this.

This effect was determined by using a circuit as shown by figure 9 where A, B, and C were the terminating resistors and the other network utilized to measure the vector sum of the line-to-ground voltage. When A, B, and C were 200, 300, and 300 ohms respectively, providing a resultant resistance of 150 ohms between lines and between each line and ground, the line-to-ground voltage was 240 microvolts. When B was short-circuited, C made equal to 600 ohms, and A equal to 200 ohms, providing a line-to-line resistance of 150 ohms and 150 ohms from one line to ground, the line-to-ground voltage increased to 1,920 microvolts. This impedance unbalance resulted in a line-to-ground voltage that was three times as great as the line-to-ground voltage obtained with a balanced 600-ohm network. This test probably produced a greater unbalanced condition than will exist in practice. However, it does show the necessity of considering unbalanced systems in the field.

Field measurements on unfiltered devices also indicate that, because of the impedance unbalances of supply systems, the networks used for measuring the noise-influence factor should have impedances greater than the average line impedances measured in the field. Figure 10 shows the ratio between the noise-influence voltage produced by a motor when terminated with a 600-ohm network and as measured on various supply lines. In this figure the ordinates are the average of the voltage measurements taken at three frequencies in 20 residences. It may be seen by this curve that 50 per cent of the cases had 25 per cent or more of the voltage measured on a 600-ohm network. Twenty per cent of the cases had 60 per cent or more of the voltage measured on the 600-ohm network. If this motor had been measured on a 150-ohm network, 50 per cent of the cases would have had a voltage on their supply line that would have been 100 per cent or more of the voltage measured when using a network.

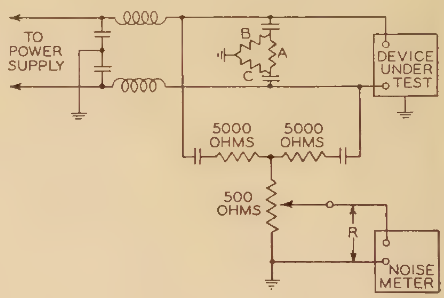


Figure 9. Circuit used to determine the effect of unbalancing the terminating impedance

Circuits Used for the Measurement of Radio-Noise-Influence Voltage at the Terminals of Apparatus Normally Connected to Single-Phase Domestic Supply Lines

The auxiliary devices and detailed methods of measurement contained in this paper have been developed primarily for the 550–1,500-kilocycle broadcast band. It is probable, however, that

the same methods can be used for measurements at frequencies higher than this, but since the problem of measurement at these higher frequencies is now in the developmental stage, the scope of this paper, so far as detailed measurement procedure is concerned, is limited to frequencies below 1,600 kilocycles.

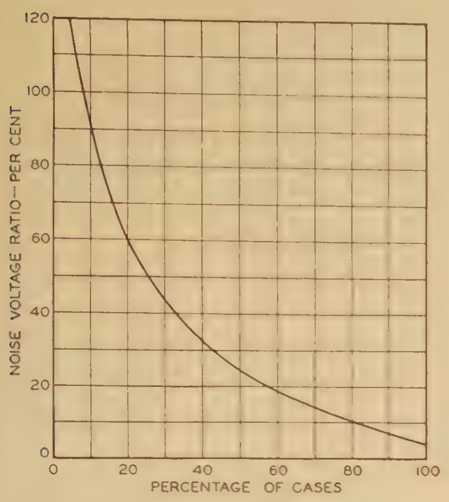


Figure 10. Per cent of noise-influence voltage existing on supply lines

The measurement of noise-influence voltage at the terminals of single-phase low-voltage apparatus such as motors, appliances, etc., is accomplished by a circuit arrangement as shown in figure 11.

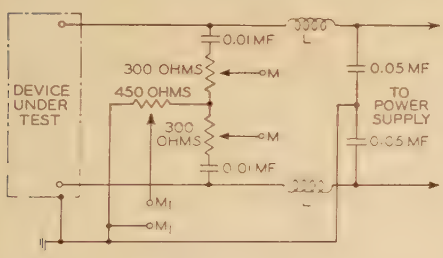


Figure 11. Circuit for the measurement of noise-influence voltage produced at the terminals of single-phase low-voltage devices

M-M—Terminals for line-to-line measurements
M_1-M_1—Terminals for line-to-ground measurements
L—Radio-frequency choke coils

Measurement of the line-to-line voltage (E_L) is made by connecting the radio-noise meter across the terminals *M-M*. This voltage may be obtained by measuring the voltage across a known portion (R) of the 600-ohm resistance between lines. This measured voltage is multiplied by $600/R$ to obtain E_L.

Measurement of the line-to-ground voltage (E_G) is made by connecting the radio-noise meter across the terminals M_1-M_1. This voltage may be obtained by measuring the voltage across a known portion (R) of the 450-ohm resistance. The measured voltage is multiplied by $600/R$ to obtain E_G.

This network is constructed with resistors that are noninductive at the radio frequencies employed in the measurements. These resistors may be of the metallized filament or carbon type commonly used in radio receivers. They should preferably be mounted with the coupling capacitors in a nonferrous metallic case. The resistance values should not differ from the specified values by more than five per cent plus or minus. Furthermore, the resistance between one line terminal and the ground terminal should not differ by more than one per cent from the resistance between the other line terminal and the ground terminal. Taps for suitable ratios can be secured by proper selection of resistor units.

It is necessary that the radio noise already existing in the supply circuit independently of the apparatus under test should not be included in the measurements and that the normal impedances existing between the supply lines and ground should not modify, in any essential respect, the characteristics of the measuring circuit. These two results are achieved by inserting in each supply lead between the measuring circuit and the terminals of the supply line a choke having a radio-frequency impedance of not less than 5,000 ohms at the frequency of the test. The chokes must be so designed that any drop in the supply voltage due to the load current of the apparatus does not cause the terminal voltage to fall below the normal rating of the apparatus.

Method of Making Measurements

The frame of the apparatus is normally grounded.

The final reading is the mean of the values measured during a period of not less than ten seconds.

In the case of apparatus having noise-influence voltages of the nature of impulses with long intervals between them, the reading is the mean of the values of ten impulses.

The network should be connected to the supply circuit by a twisted pair of leads 24 inches long and to the noise meter by leads not exceeding 4 inches.

It has been the experience to date that it is necessary to ground the device under test if comparable results in various locations are to be obtained. However, for apparatus that is normally ungrounded in service the grounding of the apparatus may increase considerably its apparent ability to produce noise. Because of the lack of information on this subject it is desirable to include in this paper the precautions that must be taken when measuring ungrounded apparatus.

In order that the capacitance to ground of apparatus tested ungrounded shall be

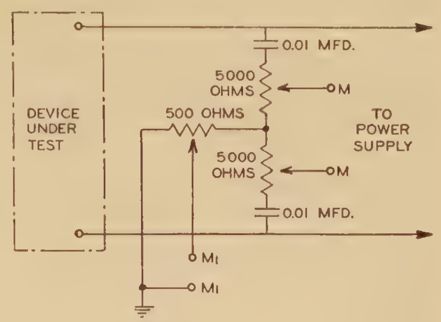


Figure 12. Circuit for the measurement of noise-influence voltage on equipment in the field

M-M—Terminals for line-to-line measurements
M_1-M_1—Terminals for line-to-ground measurements

standardized for the purpose of measurement, the apparatus under test should be placed 15 inches above the metallic floor of the test room in an insulated position. The distance to the walls of the room should not be less than 15 inches. The radio-noise meter, networks, and the person in charge of the test should be at a distance greater than 15 inches from the apparatus. If a shielded room is not available, the apparatus should be placed at a height of 15 inches over a grounded metal plate which is not less than seven by seven feet.

Circuit Used for the Measurement of Noise-Influence Voltage at the Terminals of Low-Voltage Three-Phase Equipment

A network similar to that used on single-phase apparatus may be used for three-phase systems. The network consists of three 300-ohm resistors connected in Y with a 500-ohm resistor connected from the neutral to ground. This arrangement provides a network with 600 ohms between phases, and 600 ohms between ground and all phases in parallel. The line-to-line voltage (E_L) between any two phases may be obtained by measuring the voltage across a known portion (R) of the 600-ohm resistance between the lines. This measured voltage is multiplied by $600/R$ to obtain E_L.

The line-to-ground voltage (E_G) may be obtained by measuring the voltage across a known portion (R) of the 500-

ohm resistance, and multiplying the measured voltage by $600/R$ to obtain E_G.

Measurement of Radio-Noise-Influence Voltage on Equipment in Normal Service

In normal service the noise-influence voltage of apparatus cannot be measured accurately by the networks previously described because of the possibility of these networks changing the impedance of the load circuit. Consequently, a measuring network having little effect on the impedance of the load should be used. Among those types of apparatus that require different networks are telephone equipment, complicated power switchboards, supply lines, etc.

A network which can be used for measurements on such systems is shown in figure 12. It is to be noted that this circuit is fundamentally the same as the network used for single-phase measurements, differing only in the change of

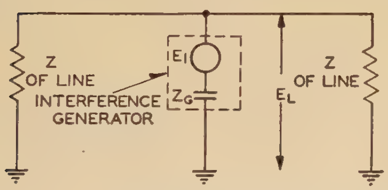


Figure 13. Schematic circuit of a typical high-voltage interference generator

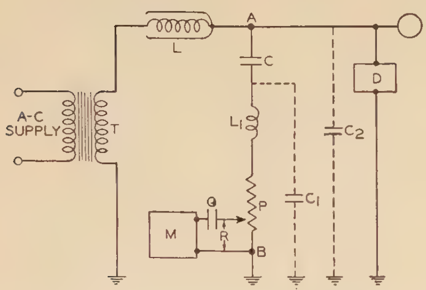


Figure 14. Circuit for the measurement of the noise-influence voltage produced by high-voltage devices

T—Testing transformer
L—Radio-frequency choke, not less than 20,000 ohms at frequency at which measurement is made
M—Radio-noise meter
C—Coupling capacitor, not less than 0.0025 microfarad
G—Dummy antenna
D—Device under test
P—Potentiometer or tapped resistor, 600 ohms resistance, nonreactive
L_1—Inductance between capacitor and potentiometer; ten microhenries, approximately
C_1—Stray capacitance on potentiometer side, not over 50 micromicrofarads
C_2—Stray capacitance on bus side, not over 60 micromicrofarads

circuit constants and omission of filter chokes.

By connecting the radio-noise meter to terminals *M-M*, the voltage across a known portion (R) of the 10,000-ohm resistance between lines can be measured. This measured voltage when multiplied by the conversion factor $10,000/R$ gives the noise-influence voltage between lines.

The line-to-ground noise-influence voltage is obtained by connecting the radio-noise meter at points M_1-M_1 across a known portion (R) of the 500-ohm resistor. When the lines are considered jointly, their resistance to ground is 3,000 ohms; thus the conversion factor for the line-to-ground measurement is $3,000/R$.

Radio-Noise-Influence Voltage of High-Voltage Apparatus

The radio-noise voltage produced by high-voltage apparatus is influenced by the same means as the low-voltage devices. It is propagated in the same fashion and the difficulties of determining the radio-noise effect on receivers are as great if not greater than from low-voltage devices. Consequently, it is necessary, as it is on the low voltage, to measure the noise-influence voltage from this type of apparatus on a standard network.

The noise-influence voltage produced by high-voltage equipment depends upon the internal impedance of the apparatus and the line impedance. An interference generator and its load impedance is shown by figure 13. All high-voltage apparatus generally has an impedance to ground at broadcast frequencies that is larger than the line impedance to ground. Because of this condition, the line impedance affects the transmission line-to-ground voltage E_G. For open-wire lines the impedance Z is between 400 and 600 ohms unless the line is shorter than 10 or 12 wave lengths.

A circuit similar to figure 14 has been used by a number of manufacturers to determine the noise-influence voltage of line apparatus, such as insulators, bushings, and fuse cutouts.

Because of the effect of the distributed capacitances of the high-voltage conductor and coupling capacitor it is necessary to limit these distributed capacitances to the values shown in figure 14 in order that the error be kept under ten per cent at 1,000 kilocycles, where the majority of the measurements are made.

A simplified circuit to show the effect of these distributed capacitances on the voltage measured is shown by figure 15. It is the same as figure 14 except the impedance of the choke coil and transformer

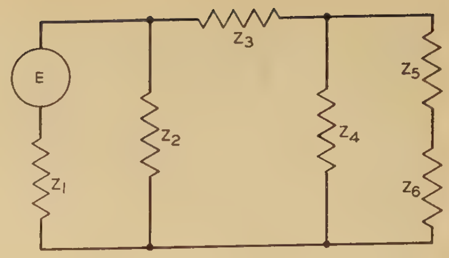


Figure 15. Equivalent circuit of figure 14

E—Voltage produced by device
Z_1—Internal impedance of device
Z_2—Impedance of stray capacitance C_2
Z_3—Impedance of coupling capacitor
Z_4—Impedance of stray capacitance C_1
Z_5—Impedance of series inductance
Z_6—Terminating resistance

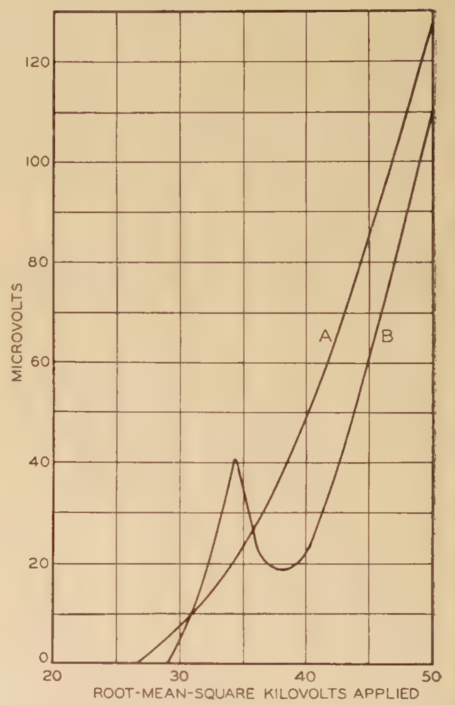


Figure 16. Effect of power-supply wave form

A—Corrected wave form
B—Distorted wave form

has been neglected. If the choke coil in series with the transformer has the impedance specified, this part of the system can be neglected.

The voltage appearing across the resistance R figure 14 (Z_6 figure 15) is:

$$E_{Z_6} = E\frac{Z_2Z_4Z_6}{Z_{11}Z_{22}Z_{33} - Z_{11}Z_4^2 - Z_{33}Z_2^2}$$

where:

$$Z_{11} = Z_1 + Z_2$$

$$Z_{22} = Z_2 + Z_3 + Z_4$$

$$Z_{33} = Z_4 + Z_5 + Z_6$$

From the foregoing, it will be noted that stray capacitances will introduce

errors, which must be given consideration in the design of a circuit such as shown by figure 14. If it is assumed that the voltage that would be measured with a pure resistance of 600 ohms across the device is E_R, then the error in per cent introduced by the system as shown by figure 14 is $\frac{E_R - E_{Z_0}}{E_R} 100$.

Effect of Power-Supply Wave Form on the Noise-Influence Voltage

Tests in the laboratory have shown that supplying a distorted 60-cycle voltage wave to the testing transformer will produce erroneous measurements. Curve *A* of figure 16 shows the noise influence produced by a treated pin-type insulator when the testing transformer was supplied by a system that contained a high percentage of harmonics. The source of voltage for this test was such as to result in a change in both the phase relationship and per cent magnitude of the various harmonic components for various values of root-mean-square voltage readings.

Correcting curve *A* to agree with the measured crest voltage readings did not materially improve the appearance of this curve.

The testing transformer was then supplied from a motor generator set and the curve *B* as shown by figure 16 was obtained.

Field Applications

In the preceding paragraphs radio-noise meters and methods of measurement have been described in detail. With the instruments available, and with the development of a suitable measuring technique, definite progress can be made by those engaged in the investigation and mitigation of noise phenomena.

Power companies and other agencies which have used noise-measuring equipment in the field have found it to be valuable in a number of ways, some of which are enumerated as follows:

1. Investigation and analysis of complicated noise problems on transmission and distribution systems.

2. Quantitative determination of noise characteristics of electrical apparatus and appliances for the purpose of determining their suitability from a noise standpoint.

3. Analyses of situations where special devices have been applied for mitigating noise effects.

4. Accumulation of data for establishing acceptable noise levels. Examples of the foregoing applications are given in the following paragraphs:

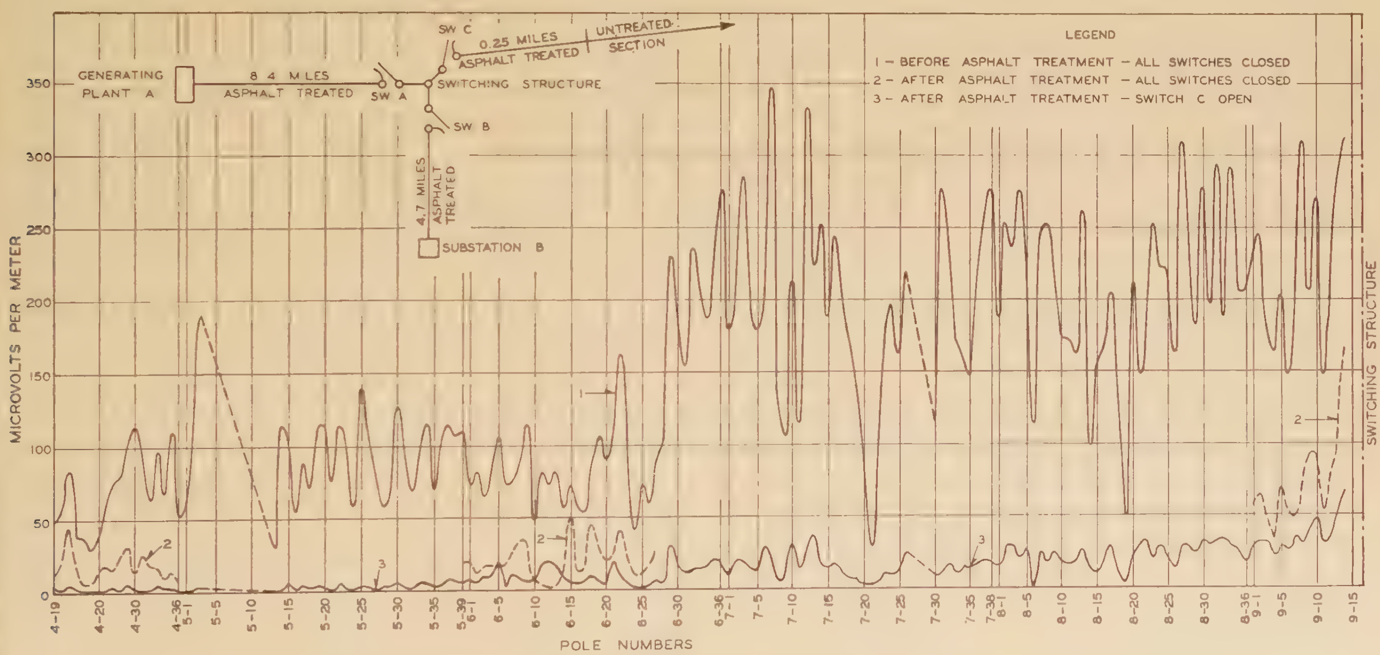
Measurement of Noise Along Transmission Lines

Figures 17 and 18 show, in graphical form, measurements made along 66-kv pin-type transmission lines where asphalt emulsion was applied to the heads of the insulators so as to close all voids between the surface of the insulator and the energized conductor and tie wires. Figure 17 covers a situation where measurements were made over a 5-mile section of the line before and after the asphalt application. A total of approximately 13 miles of line was treated between the generating station marked *A*, and the substation marked *B*. At a point 8.4 miles from the generating station there is a switching structure from which point a tap line extends for approximately 20 miles to another generating station. Except for approximately one-quarter of a mile from the tap structure, this line was not treated with asphalt at the time the measurements were made.

The explanation of the higher noise level in the sixth to ninth miles lies in the fact that this particular pole line carries both 66- and 11-kv circuits arranged in vertical configuration with the 66-kv circuit occupying one side of the pole and the 11-kv circuit the other side. Measurements were taken with the noise meter placed in a car with the antenna rod mounted on the side window. As a result, the 11-kv circuit was nearest the car up to pole 6-27 and probably shielded the higher-voltage circuit to some extent, while beyond this point the conditions were reversed. In making the measurements the car was always headed in a direction such that the rod would be on the side toward the pole line. Measurements were taken at each pole at an approximate distance of 20 feet transverse to the center of the line, and care was exercised to maintain this separation at the various pole locations.

Since the installation of the noise meter in the car would be expected to affect the measurements as compared to operating the noise meter with a standard rod as a unit on the ground, an antenna

Figure 17. Noise measurements along a transmission line—case I



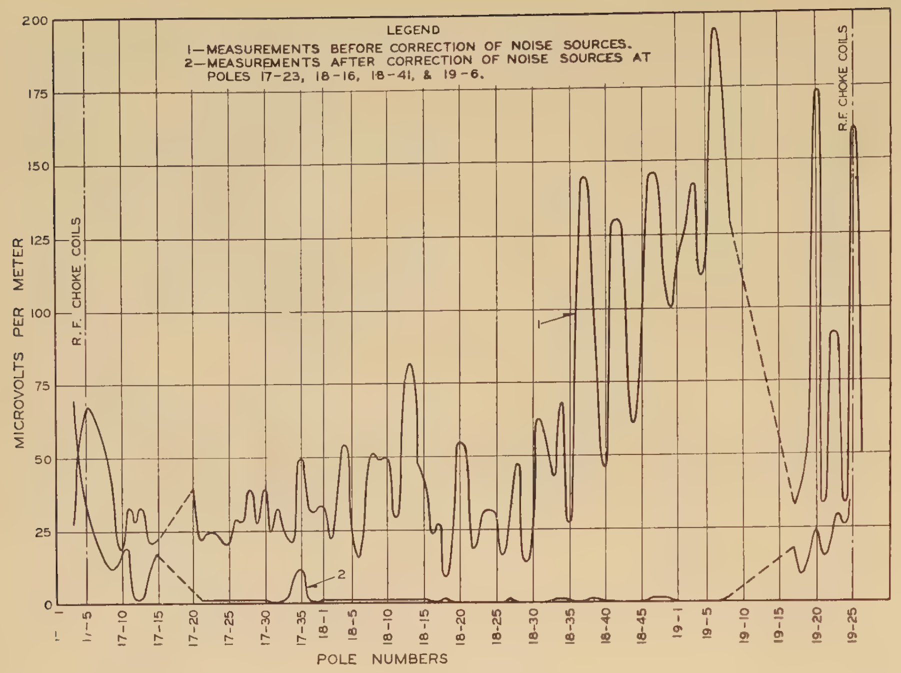


Figure 18. Noise measurements along a transmission line—case II

factor was secured in the following manner: A pole location was selected and a measurement made with the equipment installed in the car. A mark was placed on the road directly under the rod antenna, after which the instrument was removed and the car run ahead approximately 50 feet. The instrument was then placed on the ground in a position so that the rod was in the same vertical line as when mounted on the car, after which another measurement was taken. The second measurement divided by the first, gave an antenna factor for the particular frequency used and all measurements made with the measuring equipment in the car were multiplied by this factor. Aside from the quantitative results obtained in reducing the noise level the measurements indicated that a higher noise level existed in the eighth and ninth miles and beyond, probably due to inadequate asphalt coatings, and that the closing of switch *C* on the untreated tap line, raised the noise level all along the asphalted section, thus showing the results of noise propagation along the line from a distant source.

Figure 18 shows a somewhat different situation than the one just described. In this case a smaller section of line was treated with asphalt emulsion, with the addition of line-type radio-frequency choke coils installed at each end of the treated section, to attenuate the noise generated in the adjacent untreated sections. About two years after this job was completed, the noise along this line attained very high levels with the result that measurements were made along the line as shown on curve 1. These measurements indicated a source of noise at pole 19-6 with less severe disturbances originating at other points. Due consideration, however, had to be given to the possibility of reflections from the choke coils. It developed that an insulator at pole 19-6 was found to have cracks in two of the shells which gave rise to severe noise. Incidental cases were found also at poles 17-23, 18-16, and 18-41. The correction of these conditions resulted in curve 2, which indicates a very low noise level for this type of line. In making these measurements the same precautions were taken with respect to lateral distance from the line and the determination of an antenna factor as outlined in the discussion of figure 17.

Measurements of Low-Voltage Appliances

In the measurement of radio noise produced by low-voltage electrical appliances, it is desirable to utilize the information in such a way that it will be possible to rate these devices according to their radio-noise effects when operated in a home or place of business. This feature applies also to noise levels of high-voltage equipment and their relation to reception in the home, but the data on this phase of the subject, at present, are somewhat meager. This discussion, consequently, while applying in principle to all classes of apparatus, will refer specifically to the use of appliances in the home.

In analyzing any case involving interference with radio reception, the question of signal-to-noise ratio must be given consideration. In applying the reasoning prompted by this conception of the problem, it follows that reception can be improved either by increasing the signal level or by reducing the noise. Obviously there are limits beyond which each of

Table I. Radio-Noise Measurements, Low-Voltage Motor Appliance

Kilocycles	Station	Noise-Influence Voltage* Line-Ground Grounded	Noise-Influence Voltage* Line-Ground Ungrounded	Noise-Influence Voltage* Line-Line Grounded	Residence Measurements Line-Ground†	Residence Measurements Noise Voltage on Antenna	Residence Measurements Signal Voltage on Antenna	Residence Measurements Signal-to-Noise Ratio (Decibels)	Residence Measurements Quality Reception	Noise Voltage on Antenna (Per Cent) Noise-Influence Voltage Line-Ground Grounded	Noise Voltage on Antenna (Per Cent) Noise-Influence Voltage Line-Ground Ungrounded	Noise Voltage on Antenna (Per Cent) House Wiring, Line-Ground
610	*M*	1,200	160	208	585	107	396	11.4	*E*	8.9	66.6	18.3
660	*N*	1,280	170	188	612	97	140	3.0	*F*	7.6	58.2	15.8
710	*O*	1,310	184	166	610	79	860	20.8	*C*	6.0	42.9	12.7
760	*P*	1,200	207	145	370	30	1,240	32.3	*A*	2.5	14.5	8.1
830	*Q*	1,120	223	123	153	13	290	27.0	*B*	1.2	5.8	8.5
860	*R*	1,120	220	117	125	10	350	30.8	*A*	0.9	4.6	8.0
1,020	*S*	1,270	240	84	93	6	352	36.2	*A*	0.5	2.5	6.4
1,170	*T*	1,370	305	84	40	9	435	34.2	*A*	0.7	3.0	22.5
1,200	*U*	1,380	318	85	25	9	198	27.4	*B*	0.7	2.8	36.0
1,440	*V*	1,500	255	130			12,300		*A*			
Average		1,275	228	133	290	40				3.1	17.5	13.8

* In accordance with figure 11. † In accordance with figure 12.

these factors cannot go, these being dictated by geographical location, local conditions, the status of the art, and other considerations. While opinions differ to some extent, a number of measurements have indicated that where the signal-to-noise ratio is 30 decibels or greater, satisfactory reception is obtained. With decreasing values of signal-to-noise ratio, reception becomes increasingly unsatisfactory, finally reaching a point where all program reception is impossible when the signal-to-noise ratio is zero decibels or lower.

Table I shows a tabulation of a number of measurements made under various conditions on a motor-driven electrical appliance. The data include measurements made from line to ground (E_G) and from line to line (E_L) in accordance with the circuits shown in figures 11 and 12. All measurements of noise in the residence were made at frequencies adjacent to the broadcast-station channels, the noise at the latter frequencies being obtained by interpolation. Other measurements include the noise voltage from the customer's house wiring to ground, noise on the customer's antenna, signal on the antenna, signal-to-noise ratio in decibels, and quality of reception. The latter item is intended to indicate the reaction of the listener to various signal-to-noise ratios, and it has been found convenient to express these aural effects as follows:

A—Entirely satisfactory

B—Very good, background unobtrusive

C—Fairly satisfactory, background plainly evident

D—Background very evident, but speech easily understood

E—Speech understandable only with severe concentration

F—Speech unintelligible

By referring to table I it will be noted that a definite relation can be established between the noise-influence voltage and the results in a residence for a particular appliance. It has been found that even with the same appliance, results will vary in other residences. The data collected by the Joint Co-ordination Committee on Radio Reception of the EEI, NEMA, and RMA show that the relationship between noise measured at the factory and on the customer's antenna varies over a very wide range. This is due to such factors as the coupling between the antenna and supply system, the electrical characteristics of the house wiring system, the susceptibility of the radio receiver to noise pickup by means other than the antenna connection, and finally, the field intensity of the radio station being received. Through the accumulation and analysis of a considerable amount of data, eventually it will be possible to determine generally acceptable noise-influence voltages for appliances and other electrical apparatus. In making a study of this character it must be recognized that it is not economically feasible, and in many cases practically impossible, to select limiting noise-influence voltages which will satisfy all conditions and locations. As a result, limits that may be acceptable generally will have to be recognized as taking care of a certain percentage of cases rather than all cases.

Table II. Measurements of Signal and Noise Voltage on Antenna Systems

Kilocycles	Station	Signal: Conventional	Signal: Noise Reducing	Noise: Conventional	Noise: Noise Reducing	Signal-to-Noise Ratio (Decibels): Conventional	Signal-to-Noise Ratio (Decibels): Noise Reducing	Improvement, Noise Reducing Over Conventional
610	*M*	336	450	35	15.5	19.5	29.1	9.6
660	*N*	310	143	43	12	17.1	21.5	3.4
710	*O*	930	695	51	9.5	26.1	37.1	11.0
760	*P*	1,790	1,230	62	8	29.2	43.5	14.3
830	*Q*	530	570	89	7	15.5	38.0	12.5
860	*R*	450	336	106	8	12.5	32.1	19.6
1020	*S*	470	2,400	90	59.5	14.1	32.0	17.9
1170	*T*	560	1,570	102	33.5	14.9	33.5	18.6
1440	*V*	260	120	126	34.5	6.0	11.0	5.0

Measurements on Antenna Systems

In the foregoing paragraphs, reference has been made to the signal-to-noise ratio and to the coupling between the antenna and house wiring system. One method of increasing the signal-to-noise ratio is by reducing this coupling by means of a noise-reducing antenna system of suitable design and proper installation. Quantitative data to compare one antenna arrangement with another may be obtained by measuring both signal and noise separately on the two antenna systems and determining the signal-to-noise ratios for each antenna arrangement. Since the proper functioning of most noise-reducing antenna systems requires that the pickup section of the antenna be located beyond the intense portion of the noise field, the noise meter can be used to advantage in determining the best location for the antenna. This may be accomplished by making a survey at various points on the premises, using the noise meter and its associated antenna rod. The final results can then be checked after the antenna is installed.

An example of the data which may be secured and the results which can be obtained, is shown in table II. In this installation, the conventional antenna was an inverted L type with a 60-foot flat top and a lead-in located 40 feet from the overhead line carrying the disturbance. The noise-reducing antenna consisted of a vertical wire 37 feet long located 100 feet from the overhead line carrying the disturbance. A coupling transformer was mounted near the ground level at the lower end of the vertical antenna with a 12-inch lead to a ground pipe. From this point a twisted-pair transmission line, laid on the ground for the test, ran to the radio set in the house where another coupling transformer was installed directly at the antenna and ground terminals of the set. The conventional antenna was removed during the period of making measurements on the noise-reducing antenna. As in the case of table I, noise measurements were made at other frequencies and interpolated for the broadcast channels.

It will be noted that the signal-to-noise ratio was increased in varying degrees from 3.4 to 19.6 decibels when using the noise-reducing antenna and that on the basis of approximately 30 decibels signal-to-noise ratio, seven out of the nine stations involved were received satisfactorily with the noise-reducing antenna, while only one could be placed in that category with the conventional antenna arrangement. These data are given to indicate the application of the noise meter to a given situation rather than to show the maximum attainment possible with a noise-reducing antenna system. Under more favorable conditions with respect to antenna location and other factors, a much greater increase in signal-to-noise ratio would be a likely possibility.

Discussion

J. J. Smith (General Electric Company, Schenectady, N. Y.): The specifications for an instrument for measuring radio noise and the description of the methods of measurement given by the authors in this paper should be of considerable help to those who have to study the problem of radio interference. It is hoped that this work done under the Joint Co-ordination Committee on Radio Reception of EEI, NEMA,

and RMA will tend to produce a uniformity in the methods used by different workers and encourage measurements along the standard procedure.

In many cases of investigation of complaints of radio interference due to power equipment the only type of measurement made is to listen with a radio set. The data thus obtained, however, are not of great assistance since they tell only the relative value of the interference and the radio signal and do not give the actual value of either.

The signal field strength available for radio reception varies considerably from place to place. Thus, as far as radio reception is concerned, in a locality where the field strength is of the order of thousands of microvolts a given piece of power equipment might be used without affecting radio reception. However, when the same piece of equipment is used in a locality where the field strength of the radio signal is of the order of a few microvolts it might make reception difficult. Thus it is evident that the field strength at the point of reception is an important part of the radio-interference problem, and it is only by having a definite measure of its magnitude and also a knowledge of the magnitude of the noise-influence voltage produced by the device that the best solution can be obtained.

Another advantage of this new meter is that it is expected it will be available at a lower cost than the meters previously used. This should result in its being more widely used and thus assist in obtaining data on both the signal strengths at the point of reception and the noise-influence voltage of the electrical apparatus in the same location together with the resulting radio reception.

Similar work on studies of the problem of radio interference has been going on in Europe and a committee (CISPR) of the International Electrotechnical Commission has developed standards for a radio-noise meter quite similar to the one described in this paper. However, there are certain differences and I should like to ask the authors what these differences are and the reasons why it did not appear desirable to make the two meters the same.

Charles M. Burrill (nonmember; RCA Manufacturing Company, Inc., Camden, N. J.): The "quality of reception" ratings listed in table I are based on a subjective scale of values devised by the writer in 1934 for use in an unpublished research on broadcast reception at ultrahigh frequencies. This scale has been found useful within the RCA organization in a number of radio-noise and interference investigations. However, the figures in table I are the first to be published comparing ratings on this subjective scale with signal-to-noise ratios determined objectively with a radio-noise meter.

In 1936 we made a few tests to correlate the readings of a quasi-peak noise meter with our "quality of reception" ratings. The results of these tests were communicated to the Joint Co-ordination Committee on Radio Reception of RMA, NEMA, and EEI, but it was not possible to make at that time a sufficient number of the time-consuming listening tests to warrant the publication of definite conclusions. It is gratifying to note the agreement between our figures and those given in table I, despite the fact that different noise meters and different noises were involved.

We found average quality ratings corresponding to the signal-to-noise ratios given in the following table:

Signal-to-noise ratio (decibels)	+28	+8	+3	
Quality	*B*	*B*	*B*	
Signal-to-noise ratio (decibels)	−10	−20	−34	−47
Quality	*C*	*C*	*D*	*E*

All but the first three ratings in table I are entirely consistent with the above values. The first three ratings correspond to considerably poorer quality of reception than would be expected from our data. I believe the explanation of this is, that we used a noise of a more impulsive nature than the noise of an average commutator motor, and that our noise meter may have given to brief high peaks of noise relatively more weight than the instrument used in obtaining the data of table I.

The above partial agreement and partial disagreement, and the necessity for explanations are typical of experience when quantitative studies of interference are attempted. They illustrate why standardization of method is the greatest need in this field. The work reported in the present paper is a splendid and important contribution toward filling this need.

Automatic-Gain-Control Time Constants

In the radio-noise meter described in the paper, in which a logarithmic scale is obtained by "automatic gain control" action, the function of the indicating meter is twofold; first, to measure a change in output, and second, to measure a change in gain which is produced by the change in output through feedback. The input corresponding to a given indication depends on both of these. If now the time constants determining the transient response of the gain-changing circuit are not the same as those determining the transient response of the indicating meter, the actual response of the instrument to noise will be a complicated function of *both* sets of time constants.

For example, if in figure 3 of the paper the time constants R_2C_2 and R_3C_3 are made 200 milliseconds as suggested in the paper, and if the charging time of C is ten milliseconds, then the response to a single isolated noise peak will be substantially as though the automatic-gain-control circuit did not exist, for C will be charged before the gain control has time to act. If this is the performance desired, then at least the time constants of the automatic-gain-control circuits should be as carefully standardized as those determining the indicating-meter action. It should be mentioned, however, that with a slow automatic-gain-control circuit there is serious danger of overloading the intermediate-frequency amplifier on impulsive noise peaks.

I believe that the time constants of the automatic-gain-control circuits should be made the same as those determining the response of the indicating meter, so that the instrument will have a truly logarithmic scale for both impulsive and sustained noises. This is accomplished by making the time constants R_2C_2 and R_3C_3 small compared with the charging time constant of C, or ten milliseconds. Some tests have indicated that this is a practical possibility.

Internal Calibrating Source

There is another possible internal calibrating source not mentioned in the paper, which I believe has received too scant consideration. In fact such a source, a relaxation oscillator, was used in a commercial radio-noise meter built in accordance with the 1932 specifications of the Joint Co-ordination Committee ("Radio Noise Meter and its Application," C. R. Barhydt, *General Electric Review*, volume 36, 1933, page 201). The method of calibration there used may not have been very satisfactory. However, I believe that the relaxation oscillator, properly designed, will be found at least as satisfactory as the shot-noise generator, and perhaps preferable to it.

There is an advantage, not mentioned in the paper, in using for a comparison standard of calibration a typical noise wave form rather than a sine wave. By so doing, changes in selectivity of the instrument are compensated for, exactly for noise wave forms of the type used, partially for other wave forms. The compensation cannot be obtained exactly for all forms of noise, because at one extreme, the peak value with noise pulses which completely overlap is proportional to the square root of the band width, whereas at the other extreme, the peak value with nonoverlapping noise pulses is directly proportional to the band width ("A Study of the Characteristics of Noise," V. D. Landon, IRE *Proceedings*, volume 24, 1936, page 1514).

Shot noise has a wave form at the one extreme, corresponding to complete overlapping of the noise pulses in the receiver, whereas a relaxation oscillator with a low repetition frequency produces a noise wave form at the other extreme, that of no overlapping. By increasing its repetition frequency the relaxation oscillator may be made to give an intermediate type of wave form, if desired.

In a large number of cases, actual noise wave forms consist of pulses repeated at twice the commercial power-line frequency (120 cycles per second), a rate too slow to cause overlapping in most receivers. Thus, a noise wave form with a repetition frequency of 120 cycles per second such as can be obtained with a relaxation oscillator, would seem more typical of radio noise than hiss such as shot noise, and therefore preferable for use in calibration.

The shot noise of a tube is very small, so that a radio-noise meter must be very sensitive if shot noise is to be used for its calibration without additional complications. This may prove a rather severe limitation to the use of shot noise for calibration, particularly for low-priced instruments.

The shot noise generated by a saturated tungsten-filament diode may be determined very accurately by measuring the average space current, although generally a correction for the finite internal resistance of the diode must be applied unless the external resistance is low. Unfortunately, a tungsten-filament tube cannot be operated from

batteries suitable for a portable instrument. Thoriated-tungsten or oxide-coated-filament tubes, which must be used instead, are much more uncertain as to saturation and noise. It seems doubtful to me whether the shot noise from such a tube can be determined any more reliably by measuring its space current than the noise generated by a properly designed relaxation oscillator can be determined by measuring its supply voltage.

The International Special Committee on Radio Interference (CISPR), working in Europe, has been investigating the design of a standard radio noise generator, and a paper describing some of their results with a relaxation oscillator used for this purpose has recently been published ("Étude et Applications d'un Générateur Stable de Tensions Perturbatrices Radiophoniques. Perturbateur Type," G. Coffin and G. Marchal, *L'Onde Électrique*, volume 17, number 204, December 1938, pages 562–74).

J. L. Clarke (Bell Telephone Company of Canada, Montreal, Que.): The authors have not mentioned whether any means have been provided in their measuring set to make the noise field audible. It has been our experience when measuring noise including several discrete and readily identifiable sounds that it is very helpful to be able to sort out the observations when one or another of the more prominent sounds is present. We have found that the addition of an audio stage and loudspeaker to the measuring set is very helpful in this connection.

W. F. Grimes (Radio Interference Engineering Bureau, Inc., Los Angeles, Calif.): The paper by C. V. Aggers and his associates presents a very complete description of instruments and methods of measurement available for the laboratory study of radio noise. Some results of comparative laboratory and field tests are also given.

It appears that the radio and electrical industries are confronted with two general problems involving the reduction of radio noise. First, the manufacturer of electrical apparatus, as is shown by the paper, has recognized the necessity for the development of radio-noise-free products. Much work has been done to devise methods which permit reproduction of laboratory results in the measurement of radio-noise-influence voltages. Second, as pointed out in the paper, measurements now made in the laboratory cannot be satisfactorily reproduced in the field due to the electrical constants of supply circuits and other such factors.

The routine investigation of radio noise in the field is in existence today on a very limited basis. So far as is known, little or no quantitative field work is being done. Funds which have been made available for field investigations, with few exceptions, have been appropriated for the immediate benefit of broadcast and electric-utility customers. This has meant the establishing of a service free to the radio listener through which improvement in radio-receiving conditions could be accomplished.

In conclusion, it would seem that closer co-operation is necessary between the manufacturers and the field agencies serving the radio listener.

When instruments and methods of measurement are devised which will permit the interpretation of laboratory results in terms of expected radio-listener satisfaction, apparatus will be produced and purchased for the direct improvement of radio reception.

W. N. Goodwin, Jr. (Weston Electrical Instrument Corporation, Newark, N. J.): In the paper reference is made, somewhat briefly, to the characteristics of the indicating instrument. It is thought that a more complete discussion of these characteristics and why the particular constants were adopted might possibly be of general interest.

In noise measurements and also in indicating sound volume, such as broadcasting-program material, the indicating-instrument pointer is continuously fluctuating, and measurements are made by estimating averages of the pointer indication, or by noting peak readings.

In view of this condition, the first question considered by the committee was whether the instrument should be overdamped, critically damped, or underdamped.

This was studied by computing the deflection-time characteristics for specific cases of the three types of motions, from the following equations of motion. These were developed and the interesting properties of the quantity n discovered by the present writer in the early years of his career as an instrument engineer.

$$\frac{\theta}{\phi}=1-\frac{\epsilon^{-\frac{2\pi nt}{T_0}}}{\sqrt{n^2-1}}\sinh\left[\frac{2\pi t}{T_0}\sqrt{n^2-1}+\sinh^{-1}\sqrt{n^2-1}\right] \quad (1)$$

$$\frac{\theta}{\phi}=1-\left[\frac{2\pi t}{T_0}+1\right]\epsilon^{-\frac{2\pi t}{T_0}} \quad (2)$$

$$\frac{\theta}{\phi}=1-\frac{\epsilon^{-\frac{2\pi t}{T_0}}}{\sqrt{1-n^2}}\sin\left[\frac{2\pi t}{T_0}\sqrt{1-n^2}+\sin^{-1}\sqrt{1-n^2}\right] \quad (3)$$

where θ = deflection at any time t, resulting from the application of a constant electromotive force to the instrument circuit, which will produce a final deflection of an angle ϕ; T_0 is the undamped period of the instrument; and n the ratio of the actual to the critical damping coefficients, which the writer has designated "specific damping coefficient."

Equation 1 applies to the aperiodic or overdamped condition, equation 2 to the critically aperiodic condition, and equation 3 to the periodic, or underdamped condition.

Equation 1 may be considered the general equation from which equations 2 and 3 may be derived by making $n=1$ or $n<1$ respectively. When this substitution is made in equation 2 it becomes indeterminate and is evaluated in the usual manner by differentiation. Equation 3 becomes imaginary and is transformed by the relations, $\sinh^{-1} j\alpha = j\sin^{-1}\alpha$ and $\sinh jx = j\sin x$.

The three curves derived from the equations are shown in figure 1 of this discussion. Curve 1 shows the overdamped condition where the specific damping coefficient $n=1.5$, curve 2 shows the critically damped condition where $n=1$, and curve 3 the underdamped condition where $n=0.825$, and the damping factor is 100, resulting in an overswing of one per cent.

The curves were computed upon the basis that the deflections of corresponding instruments reached to within one per cent of their steady-state deflection in the same time.

It will be noted that the velocity of the slightly underdamped instrument is much more uniform from zero to full-scale deflection than for the other two conditions.

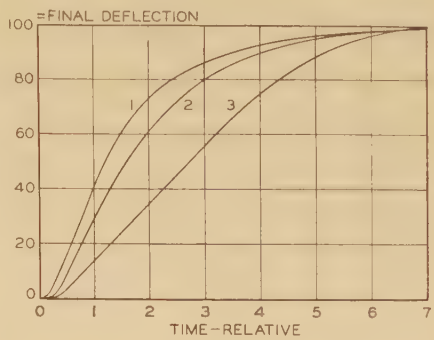


Figure 1

In the latter, the velocity is high in the lower part of the scale and diminishes rapidly in the upper part.

It is quite evident that an instrument, having a movable system giving a uniform velocity throughout its motion for a given current, would result in more correct estimates of averages and peaks than one varying in velocity. This has been proved by actual experience for a number of years in instruments for similar purposes, namely, for volume control in broadcasting. Furthermore, it results in far less eye fatigue to the reader.

For these reasons the committee adopted the slightly underdamped instrument for the noise meter.

The next question considered was that of speed of response. If the pointer action is too rapid, the eye cannot follow it; and if too slow it does not adequately follow the fluctuations in the current and gives erroneous indications. By actual tests it was found that an instrument having an undamped period of not less than 0.5 and not greater than 0.7 second, slightly underdamped, gave very satisfactory results, especially when connected into the noise-meter circuit which itself has definite time constants.

The committee thought it desirable, in order to keep the cost of the instrument within reasonable limits, to permit considerable tolerance in its constants, and for this reason specified that the undamped period may be from 0.5 to 0.7 second, and its damping factor from 10 to 100. Consideration was given to the question as to the best method of specifying response time based upon the constants just referred to. An instrument having moment of inertia, damping, and spring control does not have

a time constant similar to that possessed by a resistance-capacity circuit, or to a body heated at a constant rate, namely, the time which will reduce the exponent of ϵ in the exponential function to unity, equivalent to the time required for the quantity to reach about 63 per cent of its final value. The reason for this is that the deflection of the instrument is not only an exponential function with time but also a trigonometric or hyperbolic function, as shown in the equations given above. It would be possible, of course, to assume the time constant to be the time required to produce 63.2 per cent of final deflection as in the heat and electrical problems, but as it has no fundamental basis as it has in the latter cases, it has no especial virtue.

The time quantity which seemed to be the most practical for specifying the characteristic of the instrument, in addition to the damping, is the time required to deflect under constant electromotive force and circuit resistance from rest at zero to the final steady-current position on its first excursion. This value of time is a simple function of the damped and undamped periods and of the damping constants, any of which may be computed if the others are known, and is independent of the final scale deflection. These relations are shown in figure 2 of this discussion, in which ordi-

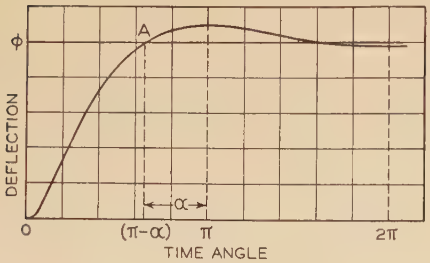


Figure 2

nates are angles of deflection, and abscissas are angles proportional to time; 2π being the angle for a complete period; and π for the half period. The angle ϕ is the steady deflection and the motion is represented by the line OA. The angle α is the phase angle of the system, equal to $\sin^{-1}\sqrt{1-n^2}$ given in equation 3. The time to complete a full period, that is through the time angle 2π, is T, where T is the damped period, and $T=T_0/\sqrt{1-n^2}$. The time angle for the deflection to A is therefore $(\pi-\alpha)$, and the time to reach A from zero is then

$$t_0=\left(\frac{\pi-\alpha}{2\pi}\right)T=\left(\frac{\pi-\alpha}{2\pi}\right)\frac{T_0}{\sqrt{1-n^2}}$$

which is the value of time by which the indicating instrument used in the noise meter is specified.

This time value for any completed instrument may be measured in several ways, for example, (1) by direct observation, using a high-speed electric stop watch; (2) by taking a motion picture of the motions of the pointer from which the time can be computed; (3) by applying an interrupted direct current, having the off and on times equal, and varying the speed of interruption until a maximum deflection of the pointer results. Then the time of a complete

Table I

Undamped Period T_0 (Seconds)	Damped Period T (Seconds)	Damping Factor k	n	Deflection Time (Milliseconds)
0.5	0.62	10	0.592	217
0.5	0.885	100	0.825	357
0.7	0.87	10	0.592	304
0.7	1.24	100	0.825	500

period, off and on, is equal to the damped period T, from which the specified time can be calculated from the equations given above.

Table I of this discussion gives the various constants of instruments having undamped periods from 0.5 to 0.7 second and damping factors from 10 to 100, computed from the above equations.

C. W. Frick (General Electric Company, Schenectady, N. Y.): The measuring circuits described in the paper have been in use for a number of years with radio-noise meters according to the old specifications. In the testing of low-voltage devices both the line-to-line and the line-to-ground radio-influence voltages are measured. The following test illustrates relations which may be found between these quantities, depending on the conditions. It also shows reasons for making the two measurements. A commutator motor was set up with choke coils in the lines, each coil having 1,700 ohms reactance at 1,000 kilocycles. The frame of the motor was grounded. First the motor was tested on the standard circuit of figure 11 of the paper. The noise-influence voltage was 2,500 microvolts line-to-line (V_L) and 4,000 microvolts line-to-ground (V_G). Referring to the equivalent circuit in figure 7 of the paper, it appears that the internal voltages E_1 and E_2 taken with respect to ground are approximately equal in magnitude and in the same direction but not in phase, since when the line impedances are equal V_L is proportional to the vector difference of E_1 and E_2 and V_G is proportional to one-half their vector sum. A later test indicates the assumption of equal magnitudes for E_1 and E_2 to be reasonable.

Next the device was connected in a circuit similar to figure 9 of the paper to try the effect of equal and unequal impedances between supply lines and ground. A delta network of 200 ohms between lines and 300 ohms from each line to ground, as in the paper, was used for the first condition. Noise voltage between lines was measured directly and noise voltage from line to ground was measured on the network of figure 12 connected as in figure 9. This gave 620 microvolts line-to-line and 1,080 microvolts line-to-ground. These values are approximately one-fourth of those measured according to figure 11, this ratio being the same as the ratio of the resistances of the networks which were 600 and 150 ohms respectively. This shows that the radio-frequency currents were controlled by the line chokes.

The next measurement was made with unequal impedances between lines and ground. One side of the line was connected to ground and a 150-ohm resistor was connected across the line. The measuring network of figure 12 was left in place. The noise voltages then became 1,250 microvolts line-to-line and 630 microvolts line-to-ground. It may be noted that the line-to-ground voltage is half the line-to-line voltage which it should be in this test because the network of figure 12 measures half the vector sum of the voltages between lines and ground and here the voltage on the grounded side is zero.

It appears from these results that the junction between E_1 and E_2 in figure 7 is practically grounded, probably through capacitances and the grounded frame. Then when one side is grounded it eliminates the voltage on that side from the circuit. The voltage across the line was the same with the ground on either side which would indicate that E_1 and E_2 are nearly equal in magnitude. In the case of equal impedances the line-to-ground voltage was proportional to half the vector sum of E_1 and E_2 or approximately proportional to either E_1 or E_2. In the case of one side grounded only one of these was acting and the voltage to ground was only half as large.

If the phases of E_1 and E_2 had been different the result would have been different. If they had been equal and opposite in direction instead of in the same direction, they would have tended to cancel each other out in the line-to-ground voltage when the impedances from line-to-ground were equal. However, when one side was grounded, eliminating either E_1 or E_2 from the circuit, the cancellation effect would not exist and the line-to-ground voltage would be about the same as in the test. Thus if E_1 and E_2 were opposite in phase the line-to-ground voltage would increase as it did in the test described in the paper. In the test described here, however, it decreased.

If E_1 and E_2 are opposite in phase, their effect is additive between lines. In such a case consideration of the test results indicates that under conditions of unequal impedances between lines and ground the line-to-ground voltage would not exceed half the value measured between lines provided the impedance of the line is not higher than the impedance of the network. The two quantities measured are useful for analyzing effects such as these.

In table I of the paper which gives an example of radio-noise data taken on a device and data taken in a home, the figures in the last three columns appear to be ratios between these two sets of measurements, but it is not clear what they are. It would be desirable for the authors to add an explanation of these figures and to show their use.

Further explanation would also be desirable in the case of figure 16. Can the shape of the curve for distorted voltage be explained? If the authors consider it necessary to take precautions to avoid errors attributed to voltage distortion, it would be desirable to state what these precautions should be.

Charles J. Miller, Jr. (The Ohio Brass Company, Barberton): The radio-noise meter described by the authors certainly has several desirable characteristics over those formerly available. The use of a logarithmic output meter with a range of 100 to 1 will certainly reduce the amount

of work necessary for measuring radio-influence voltages on all types of devices. The new meter will be direct reading, a decided improvement over the substitution method of measurement.

In connection with the proposed detector circuit and indicating meter, a tabulation of suitable combinations of R, C, and R_1 is given. The lowest value of R given is one megohm. Since this resistance is in series with the indicating meter, the sensitivity of this meter will have to be very high. The most sensitive portable meter with which the writer is familiar has a full scale deflection for 20 microamperes flowing through it. If used with the one-megohm resistor, the voltage across the capacitor C would have to be 20 volts to produce a full-scale reading. What is the maximum voltage that can be satisfactorily applied to the capacitor C, considering all the limitations imposed by vacuum tubes available, and what indicating-meter sensitivity is practical for this application?

The coupling circuit for use with high-voltage devices imposes three new limitations over the previous circuit. These are the upper limits placed upon stray capacitances on the bus side and potentiometer side of the circuit and the lower limit of 2,500 micromicrofarads for the coupling capacitor. A formula is given whereby one may calculate from the constants of the circuit, Ez_6, the voltage appearing across the resistance potentiometer. A second formula is given whereby the per cent error may be calculated if the load impedance into which the device is looking is different from a pure resistance. It is possible to determine all the constants of an existing circuit by measurements. While it is fully recognized that it is desirable to use a circuit meeting all the requirements, is it not practical to compute the error introduced by an existing circuit, whose parameters are known, and then to use this factor to correct all readings taken on that circuit in order to make them comparable with values that would be obtained on an ideal circuit?

E. T. Hughes (Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): In 1930 the Joint Co-ordination Committee on Radio Reception of EEI, NEMA, and RMA was appointed to study methods for improving radio reception and in particular to consider the steps necessary to co-ordinate this newer use of electricity with some of its other uses for light, heat, power transmission, and communication.

A major problem has been in the development of radio-noise test circuits for the laboratory measurement of radio-noise-influence voltages. A test circuit which could determine directly the radio-noise voltage to be expected on any receiver antenna from any electrical apparatus on test would be desirable. However, no definite method has been developed that will permit the calculation of the radio noise on a receiver antenna when the radio-frequency voltage produced by electrical apparatus is known. Therefore the solution to the problem has been to develop measuring circuits which will permit measuring the radio-noise-voltage output of electrical apparatus with a radio-frequency load simulating the load impedance of the power system. At the present state of the art the radio noise produced by any equipment can only be expressed in units measured, utilizing the coupling networks recommended by the joint co-ordination committee.

The two basic circuits which have resulted from these considerations have proved to be well adapted for laboratory work because it has been possible for investigators in different laboratories to obtain comparable results in tests on the same apparatus.

By the use of the high-voltage test circuit it has been possible for the NEMA members to recommend certain levels for various high-voltage equipments. These levels have been obtained by making measurements on new equipment and on equipment which was returned from the field. The establishment of permissible levels of radio-noise-influence voltage for all classes of apparatus will require a somewhat different approach to the problem through field tests on different systems throughout the country.

Field tests are now being conducted in the Pittsburgh area to aid in the establishment of levels for low-voltage appliances. An appliance will be tested for radio-noise-influence voltages in the laboratory, then installed in several different homes where the noise voltage on the antenna will be measured. Knowing the effective height of the installed antenna, the signal-to-noise ratio desired, and broadcast station field strength, then the tolerable noise-influence voltage will be:

$$V = \frac{Se}{R}$$

where

V = tolerable noise influence voltage
S = antenna noise factor
e = broadcast station field strength level
R = signal to noise ratio

It is expected that from these tests the antenna-noise factor for an average home may be determined.

A second set of tests has been planned on a 6,900-volt distribution system. These tests are intended to determine the attenuation, effect of reflection, the amount of radiated field, and the field intensity perpendicular to the line in terms of the actual high-frequency voltage on the transmission line. The attenuation of the noise voltage through distribution transformers will also be studied.

A comparison between the work on this subject here and abroad may be of interest to some. The noise meter conforming to the new committee specifications is very similar to the one adopted by England, France, Germany, Italy, and Belgium. The low-voltage coupling networks used in the United States are different in that we have adopted a star network compared to a delta circuit used abroad. Both networks, however, give comparable results when the impedances are the same. The joint co-ordination committee has adopted 600-ohm networks whereas the European network is 150 ohms. The reasons for adopting 600 ohms have been outlined in the paper.

The continuation of the work of the joint co-ordination committee shows promise of producing more beneficial results in the future and by universal adoption and use of this instrument and method of measurement, radio-noise levels for all types of equipment can be established.

C. V. Aggers, D. E. Foster, and C. S. Young: The supplementary information contained in the various discussions is a valuable contribution to the problem, making the paper a comprehensive description of the art of measuring radio noise.

J. J. Smith has raised the question as to why the instrument described in the paper differs from the specifications developed by the CISPR. The CISPR specifications call for a time constant on charge of 1 millisecond and on discharge of 160 milliseconds. The other differences between the instrument in the paper and the CISPR specifications are of a minor nature and will in general cause no difference in performance between the two instruments. In developing the specifications for detector time constants, consideration was given to the CISPR specifications. However, as pointed out in our paper, it is difficult to secure a charge time constant of 1 millisecond with available tubes and difficult to hold this value in production, whereas it is relatively easy to secure a 10-millisecond charge time constant and a time constant of such value may be more readily held in production of noise meters. The discharge time constant specified by the CISPR is of the same order as that of the indicating meter, and hence the indicating-meter time constant will have a large effect on the results obtained. By the use of the long time constant of 600 milliseconds suggested in our paper, a much wider permissible range of time constants for the indicating meter is provided, and indicating meters of more desirable characteristics may be secured. Furthermore, as pointed out in the paper, by largely eliminating the influence of the indicating meter, the effective discharge time constant becomes that of the circuit, and this may be more readily duplicated in production than the time constant of the meter. The ratio of charge to discharge in the CISPR specifications is larger than that of the meter described in our paper, and therefore the CISPR meter will give a higher indication on wave forms of the sharply peaked type. On wave forms approaching the sinusoid, the difference in indication between the CISPR and the joint co-ordination committee specifications will be of the order of one per cent, a relatively minor factor considering the other possible variations.

We feel that the time constants suggested in our paper will give more constant, reliable results and permit more uniformity in production of noise meters than those adopted by the CISPR.

C. M. Burrill points out that with the automatic-volume-control time constant suggested in our paper, the response on a single-pulse type of noise will depend in some degree on the time constants of the automatic-volume-control circuit. The response of the instrument will not be the true peak value on a single pulse or widely separated repetitive pulses, not only because of automatic-volume-control time constants, but also because of the detector time constants chosen. As pointed out in the reply to Doctor Smith's discussion, the detector

time constants were chosen to provide reliable and consistent results with practical tubes and circuits, rather than to provide idealized response to all types of noise. Furthermore, as pointed out in our paper, the disturbing effect of pulse types of noise appears to be less than would be indicated by their peak amplitude. It is felt that the correlation of the meter indication on such types of noises with their disturbing effects will be satisfactory with the time constants described and may in fact be better than when the time constants are chosen to give indications nearer the actual peak values. Mr. Burrill's suggestion of short automatic-volume-control time constants would be satisfactory provided adequate attenuation is provided by the automatic-volume-control filter having the short time constants he suggests. The automatic-volume-control filter must be such as to prevent the audio-frequency component of the noise present in the detector circuit from being applied to the amplifiers and there producing a modulation effect. An automatic-volume-control filter of short time constant with adequate attenuation of the audio-frequency component is considerably more complex, that is, must include more filter stages for the same attenuation, than one with a longer time constant.

Relaxation oscillators were considered in drawing up specifications on the noise meter, but experience to date with this type of oscillator was, in the opinion of the majority of the committee, such as to indicate that relaxation oscillators are not as reliable or uniform nor as readily checked in instrument use. The determination of the output of the relaxation oscillator by measurement of the supply voltage is an indirect method, and therefore not as accurate as measuring the current in a saturated diode. The advantage of a noise calibration source of a type to eliminate the selectivity influence in calibration mentioned by Mr. Burrill was also a factor influencing the committee's choice of a saturating diode as a noise source. Mr. Burrill is correct in stating that the theoretical shot noise from oxide-coated-filament tubes, such as are practical for portable noise meters, is not as readily determined as that from tungsten-filament tubes. However, in the noise meter described, oxide-coated-filament tubes are satisfactory, since they are used as a transfer standard, the initial calibration being in terms of an unmodulated sine-wave voltage. When so calibrated, it is felt that the oxide-coated-filament diode is a practical and uniform transfer standard readily determined by measurement of the space current. The difference between tungsten and oxide-coated, or thoriated-tungsten-filament tubes is that the latter two types do not have a sharp, definite saturation characteristic but saturate more gradually. Under such circumstances, the impedance of the diode must be taken into account. This impedance need not be specifically determined for the use described in our paper, since it is implicitly included in the initial calibration process.

C. J. Miller's comment emphasizes the point mentioned in our paper that a d-c amplifier may be employed to permit the use of a less sensitive meter. The use of a d-c amplifier and relatively insensitive meter is a more practical design combination than an attempt to secure a charge time constant of ten milliseconds with a resistor lower than one megohm. Battery-type tubes such as are required for portable noise meters have a rather high effective resistance when used to drive a diode and therefore consideration was not given to resistors of less than one megohm. All through the design of the instrument practical tube and circuit considerations were kept in mind in an endeavor to provide an instrument to give readily reproducible results.

The influence of capacitances in the measurement of high-voltage devices is perhaps more readily taken into account than might be indicated by Mr. Miller's comments. Such circuit capacitances are very important in television and have been studied by many investigators of late. The principles developed for television may be used in connection with other circuits where the stray capacitances are important, such as in this case the noise-measurement circuits. Among the several technical papers dealing with this problem, are the following:

"Analysis and Design of Video Amplifiers," S. W. Seeley and C. N. Kimball, *RCA Review*, January 1939.

"Transient Response of Multistage Video Frequency Amplifiers," A. V. Bedford and G. L. Friedendall, IRE *Proceedings*, April 1939.

These papers describe the principles and methods involved when uniform response characteristics are necessary over a range of the order of four megacycles, which is even greater than is required in the case of noise measurements.

J. J. Clarke inquires regarding means of making the noise audible. The provision for audible indication of the noise is a decided help in identifying the type of noise or in identifying broadcast stations when the equipment is used for field-intensity measurements. As pointed out in our paper, when the audio-frequency noise output is used for listening, the detector time constant should be of the order of 0.1 millisecond, which may be accomplished through the use of a switch reducing the value of the capacitor by a factor of 100 for listening purposes.

The specifications for the 150 to 18,000-kilocycle noise meter include a paragraph which states that a switch shall be provided to substitute for the weighting detector circuit a conventional second-detector circuit for carrier field-intensity measurements or to supply audio-frequency output which can be used for monitoring analysis with other apparatus.

Mr. Grimes pointed out the need for closer co-operation between the manufacturers and the field agencies. This has been one of the crying needs since the advent of radio but these two groups cannot co-ordinate their activities until standards on instruments and methods of measuring radio noise have been established. It will be only through the co-operation of these groups that sufficient data will be collected which will permit the interpretation of laboratory results in terms of expected radio noise.

It was pointed out by Mr. Hughes in his discussion that a series of field tests are contemplated in an attempt to obtain some conception of the correlation factor between laboratory measurements and field measurements. It is encouraging to note that such a program is under consideration. A number of such programs should permit the establishment of satisfactory radio noise levels for all types of apparatus.

The data included in Mr. Frick's discussion emphasizes the necessity for making both the line-to-line and line-to-ground measurements on low-voltage apparatus as well as choosing some definite terminating impedances for measuring the radio-noise-influence voltage.

The phase relation of E_1 and E_2 in figure 7 varies a great deal between types of machines and somewhat on even the same design of machines. The data shown in the paper is representative of what may be expected from a definite type of machine.

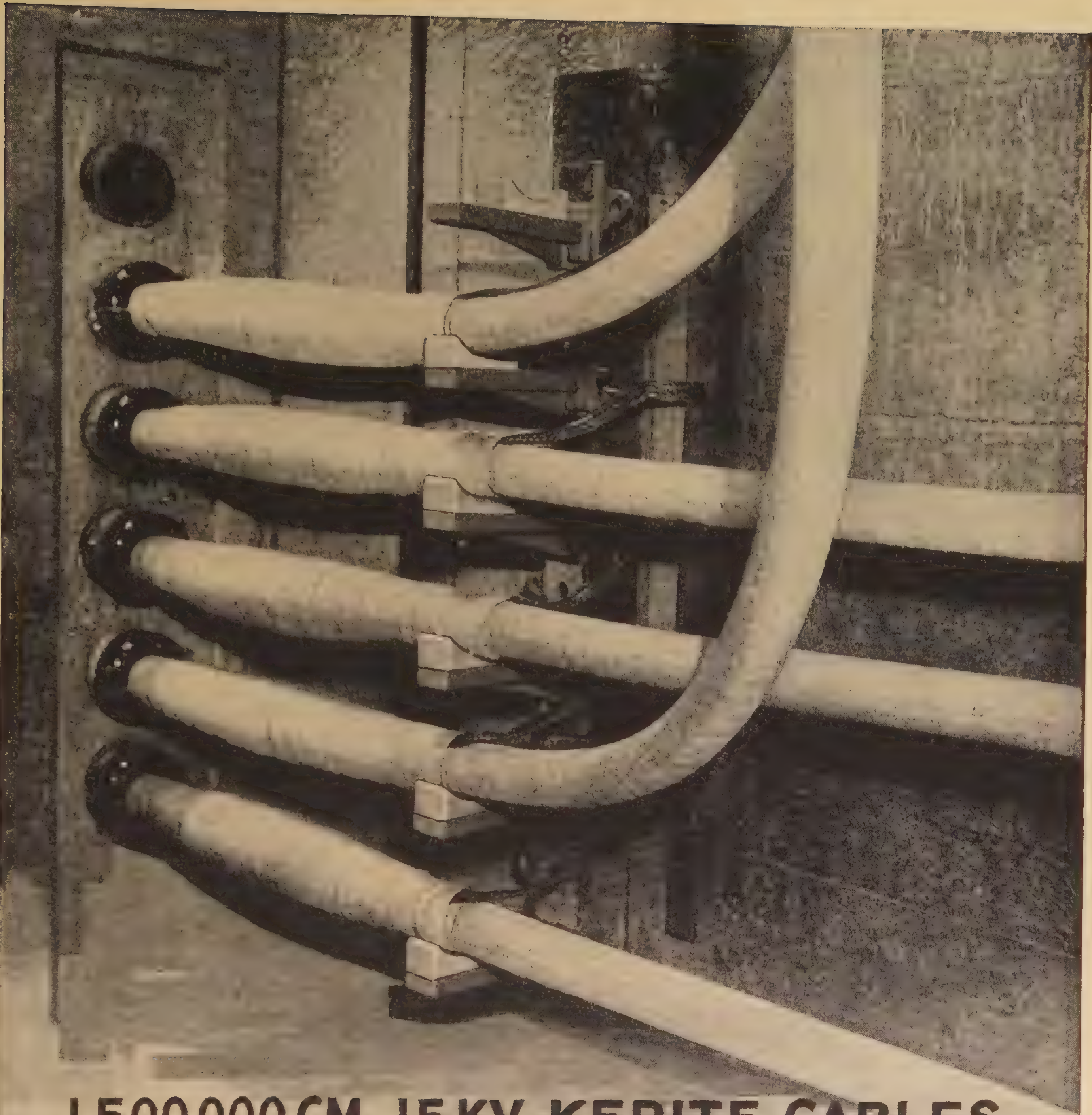
Mr. Frick stated that his tests indicated the junction between E_1 and E_2 in figure 7 is practically grounded. In practically all small commutating machines, the capacity of the windings to the frame is relatively small. There is also the impedance of the field winding between the interference generator and ground so that it would be practically impossible that the junction between E_1 and E_2 be at ground potential.

We wonder if Mr. Frick has not misinterpreted his results because if the measurement is made by figure 12 and one side of the line is grounded, the V_G could be only half of the line-to-line voltage. In other words, the line-to-line measurement is actually the line-to-ground measurement because one side of the line is grounded. The value of 1,250 microvolts appears to be correct because in the previous measurement he obtained 1,080 microvolts line-to-ground. The grounding of one side should increase this value of 1,080 as was obtained by Mr. Frick.

Mr. Frick questions table I. The caption of the last three columns was omitted in the preprint. These columns give the noise voltage on the antenna in per cent of the noise-influence voltage line-to-ground and house wiring. The collection of this type of data by various investigators will permit the establishment of noise levels for such apparatus, for instance, at 610 kilocycles (table I) the noise voltage on the antenna is 8.9 per cent of the noise-influence voltage line-to-ground with the frame grounded. If, for example, it could be determined that an average of ten per cent of the noise-influence voltage produced by low-voltage devices would be obtained at the input to the radio receiver, then it would be possible to determine the permissible radio-noise-influence voltage of a device which would permit satisfactory radio reception with any available broadcasting field-strength level.

The distorted wave shape shown by figure 16 was due to drawing leading current through the induction regulator. In the case discussed, it was necessary to eliminate the induction regulator and energize the transformer from a motor generator set. From tests to date it appears as if it will be desirable to limit the total distortion of the voltage wave to five per cent.

Mr. Goodwin's discussion is a very valuable contribution on this subject as he has covered thoroughly many of the factors given consideration while preparing the specifications of the indicating meter for the radio-noise meter.



Industrial Notes

Expansion Program for Standard Gas.—Construction of a 25,000-kw capacity addition to the Canal station of Louisville Gas & Electric Co., at Louisville, Ky., has been decided upon. Authorization of this project will result in a total of 160,000 kilowatts of additional generating capacity being under construction during 1940 by public utility operating companies in the Standard Gas & Electric Co. system, and appropriation for the Canal station addition brings the total tentative construction budget of the system for 1940 to over $40,000,000.

Roebling Appointment.—Edward D. Emerson, since 1937 district sales manager with Babcock & Wilcox Tube Co., New York City, has been appointed general manager of sales by the John A. Roebling's Sons Co., Trenton, N. J.

Lewis to Head Rectifier Division.—The manufacture and sale of selenium rectifiers in the United States has been placed in charge of George Lewis as manager of the rectifier division, International Telephone Development Co., with factory and sales headquarters at 137 Varick St., New York City. The selenium rectifier is manufactured exclusively in this country by the International Telephone Development Co., a subsidiary of the International Telephone and Telegraph Corporation. Mr. Lewis has played a prominent part in recent development work in the laboratories of the International associated companies in Europe, serving for a considerable period as commercial director of the large laboratory in Paris.

Roller-Smith Appointments.— C. Swain Lumley has been appointed district engineer of the Roller-Smith Co., Bethlehem, Pa., with headquarters in Chicago. He will cover the states of Michigan, Indiana, Illinois, Missouri, Iowa, and Minnesota, rendering engineering assistance to the company's sales agents in the territory. Mr. Lumley was formerly electrical engineer in charge of design on the Detroit new sewage treatment plant. From 1926 to 1935 he was designing mechanical-electrical engineer with Smith, Hinchman and Grylls, architects and consulting engineers, in Detroit. . . . The Electric Steel Foundry Co., Honolulu, has been appointed as Roller-Smith sales agent for the territory of Hawaii.

Expenditures for WPA Electrical Equipment.—Electrical machinery, apparatus and supplies purchased for use on WPA projects amounted to $23,191,000 during the period from the program's inception in July 1935 through September 1939, according to figures released by the Work Projects Administration. These purchases were used on a broad variety of WPA projects including construction and improvement of public facilities in almost every major category. Total WPA purchases of materials, equipment and supplies of all kinds during the 1935–1939 period amounted to $1,118,764,000 and the manufacture and fabrication of these products required, according to Bureau of Labor Statistics' estimates, more than 2,565,000 man-months of employment.

Okonite Company Appointment.—Richard S. Hayes has been appointed advertising manager of The Okonite Co., Passaic, N. J., and The Okonite-Callender Cable Co., manufacturers of insulated wires and cables. Mr. Hayes joined The Okonite Company in 1925, and since 1936 has been in charge of various sales promotion activities.

Trade Literature

Motor-Generator Sets.—Bulletin 502, 4 pp. Describes various types of motor-generator sets available in sizes up to 500-kw capacity. Reliance Electric & Engineering Co., 1088 Ivanhoe Road, Cleveland, Ohio.

Communication Home Study Course.—1940 Information Booklet, 32 pp. Describes a practical radio and communication engineering course designed for home study. Smith Practical Radio Institute, 1311 Terminal Tower, Cleveland, Ohio.

Cable Terminals.—Bulletin, 4 pp. Describes a new improved type of gasketless, soldered porcelain terminals, designed to be vacuum and pressure-tight in service, even under abnormal temperature and pressure conditions. The construction eliminates all gaskets and overcomes the problems associated with gasket leaks. General Cable Corp., 420 Lexington Ave., New York City.

Circuit Breakers.—Bulletin 4001. Describes a new, compact, type KB air circuit breaker which is capable of high speed interruption of currents far in excess of its conservative rupturing rating of 20,000 amperes, according to the manufacturer. Available in a variety of mountings, for electrical or manual operation, in ratings up to 600 amperes. I-T-E Circuit Breaker Co., 19th & Hamilton Sts., Philadelphia, Penna.

Distribution Transformers.—Catalog 40, 24 pp. Describes and illustrates a complete line of improved distribution transformers. Pocket type bushings are used on all such transformers up to 50 kva. The metallic parts of the primary bushings are porcelain enclosed, and these bushings incorporate a new mortise-type wire grip. The catalog includes transformer standards and tables for all ranges, and prices. Kuhlman Electric Co., Bay City, Mich.

Constant Voltage Transformers.—Catalog ACV-22. Describes constant voltage transformers capable of maintaining their output voltage to within a fraction of the per cent of the specified value, even though the line voltage varies as much as 30 per cent. Fully automatic, instantaneous in action, such transformers have no moving parts and require no maintenance; available in wide capacity ranges. Sola Electric Co., 2525 Clybourn St., Chicago, Ill.

Noise-Free Insulators.—Bulletin, 8 pp. Describes a complete line of "Quiet-Type" insulators for all operating voltages; illustrates the glaze-protected metallic oxides used in their manufacture. Such types are guaranteed to eliminate insulator radio-noise when installed on voltages for which they are designed. Included is a proposed table of permissible noise levels. The R. Thomas & Sons Co., Lisbon, Ohio.

A new list of available pamphlet copies of AIEE papers appears on page 10, adv. sec., this issue.

Here's the simplest way to study Generator Insulation

CENTRAL STATION engineers now recognize that a single measurement of the insulation resistance of electrical generators gives no true indication of generator leakage. The value of insulation resistance can be obtained only by a series of measurements taken at increasing time intervals over a considerable period of time. From these resistance-time curves a true picture of the condition of the insulation may be obtained.

The General Radio Type 544-B Megohm Bridge with its 500-volt power supply is the ideal instrument for obtaining resistance-time curves of any generator. Its features include:

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WRITE FOR BULLETIN 558

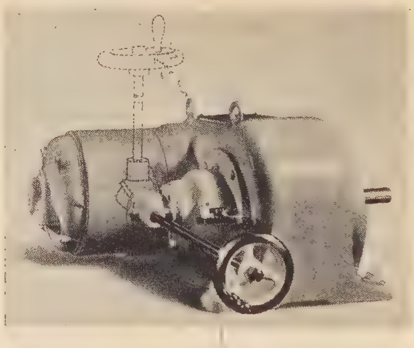
GENERAL RADIO COMPANY CAMBRIDGE MASSACHUSETTS

New Products

New Type Rotor Construction.—Offering the advantage of longer motor life with less maintenance, a new type rotor construction

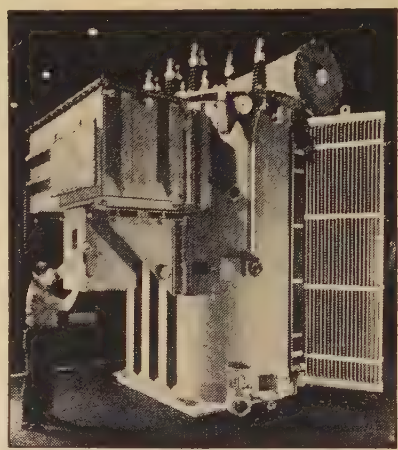
announced by the General Electric Company makes possible the use of cast-aluminum rotors in the larger sizes of double-squirrel-cage motors for high-starting-torque, low-starting-current service. Called the "Valv-amp" rotor, it employs a unique shape of rotor slot and a special method of assemblying rotor punchings to control the flow of starting current. As a result, without the use of a switch or other moving parts, current is permitted to flow in the outer squirrel-cage when the motor is started, thus producing high-starting torque. Then, when the motor comes up to speed, current is allowed to flow through the entire rotor "winding," resulting in excellent running characteristics. Above is an oblique end view, showing one arrangement of bars, end rings and fans.

Control for "Varidrive" Motors.—A new single, right angle, mechanical remote control for Varidrive motors has been developed

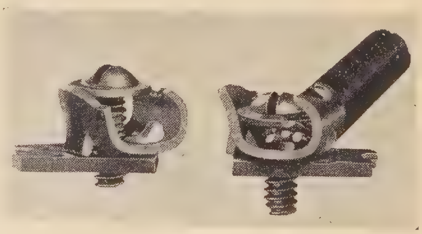


by U. S. Electrical Motors, Inc., of Los Angeles and Brooklyn. This control provides an accurate, simple means of selecting the desired operating speed of the motor when the Varidrive is mounted beneath or above the driven machine or is otherwise inaccessible. The control shaft may be extended at a 90-degree angle in any one of eight different directions, permitting the hand wheel to be placed within easy reach of the operator so that the exact desired speed can be maintained without difficulty at all times.

Load-Ratio Control.—The Allis-Chalmers Mfg. Company, Milwaukee, has introduced a new transformer load-radio control mechanism, known as type TLK, to supplement its already well-established types TLF and TLB. This new mechanism is designed for application on medium-large regulating and power transformers, single or three-phase, and can be arranged for automatic or manual control. The type TLK design has dial switches and rotary-breakers mounted on separate oil-filled compartments with complete mechanical interlocking so that the tap changing circuits are closed and opened by the breakers while changing taps. The illustration below shows the type TLK load-ratio-control mechanism mounted on a 3-phase regulating transformer for operation with an 18,750-kva, 35-kv circuit.



Connector.—This new solderless connector, developed by the Square D Company, Detroit, known as the Universal speed connector, will take from No. 14 to No. 4 wire. The connector is free to rotate around the screw, thus allowing wire to be inserted from almost any angle. This feature is important where large wires are used in a limited space. The unusual range in wire size permits the use of large wires for service drops to small 30- or 60-ampere switches. The connector is self-centering so that there is no need to wind the wire around the stud or to separate stranded conductors. As the screw is tightened, the lug is forced to one side and the wire is gripped tightly. When the tightening is completed, the screw exerts pressure against the wire on one side and the lug on the other side.



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☐ 39-121	Marti & Taylor	Wave Shape of 30- and 60-Phase Rectifier Groups
☐ 39-122	Lewis & Foust	Lightning Investigation on Transmission Lines
☐ 39-123	Alford & Pickles	Radio-Frequency High-Voltage Phenomena
☐ 39-127	Benson & Strang	12-Kv Metal-Enclosed Bus and Switch Structure
☐ 39-129	Halperin	Testing of Distribution Arresters
☐ 39-133	Boice, Crary, Kron & Thompson	The Direct-Acting Generator Voltage Regulator
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☐ 39-136	Dickerson & Mahan	Painting the Golden Gate International Exposition With Light
☐ 39-137	Kiltie	New Type of D-C to A-C Vibrator Inverter
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☐ 39-139	Hanna & Tritle	Electrical Equipment of the Steam-Electric Locomotive
☐ 39-140	Reinitz & Wiseman	A New Technique for Lead Cable Sheathing
☐ 39-141	Smith & Tenney	Temperature Survey of the United States
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Minneapolis Meeting

☐ 39-147	LeClair	Arc-Furnace Loads on Long Transmission Lines
☐ 39-148	Summers	An Unstable Non-Linear Circuit
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☐ 39-152	Maxfield, Hegbar & Eaton	Importance of Gas in Electrodes for Glow-to-Arc Transition
☐ 39-153	Swanson	Polarized Field Frequency Control of Synchronous Motors
☐ 39-154	Smith & Bostwick	Ratio Differential Protection of Transmission Lines
☐ 39-155	Hoard	Transit-System Modernization, Choice of Vehicle
☐ 39-156	Bryant & Newman	Electronic Measurement of Surge-Crest Voltages
☐ 39-157	Bryant & Newman	Measurement of Very Short Time Lags
☐ 39-158	Butler	Factors Influencing Shunt Capacitor Equipments
☐ 39-159	Holbrook & Dixon	Load-Rating Theory for Multi-Channel Amplifiers
☐ 39-160	Kurtz	Dynamic Characteristics, Single-Phase Induction Motor
☐ 39-161	Parsons	Vaults for A-C Secondary Networks
☐ 39-162	Stephens & Gehrenbeck	Corrosion of Fine Copper Wires Carrying a Potential
☐ 39-163	Willey	Emergency Radio as Safeguard to Telephone Service

Scranton Meeting

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☐ 39-165	Bell	Lightning Investigation on a 220-Kv System, III
☐ 39-166	Caldwell	Electrical Apparatus in the Steel Industry
☐ 39-167	Armstrong	NEMA Resistors for Motor Starting and Speed Control
☐ 39-168	Penney	Temperature Rise of Electrical Apparatus
☐ 39-169	Compton	Class B Insulation for Auxiliary-Type D-C Motors
☐ 39-170	Edmunds	Adjustable-Speed A-C Motors
☐ 39 171	Beavers	Selection of Distribution Transformer Size
☐ 39-172	Hentz & Thielman	Power Supply for Suburban Areas
☐ 39-173	Camilli	Current Transformer Design

Winter Convention

☐ 40-4	Torchio	Railway Power Supply
☐ 40-5	Bellaschi & Palermo	Analysis of Transient Voltages in Networks
☐ 40-6	AIEE Committee Report	Report on Power Generation
☐ 40-7	Alexanderson, Edwards & Bowman	Dynamoelectric Amplifier for Power Control
☐ 40-8	Foust & Scott	Breakdown Tests on Oil-Treated Paper-Insulated Cable
☐ 40-10	Fisher	The Design Characteristics of Amplidyne Generators
☐ 40-12	Morgan, Brown & Schumer	Induction Motor Characteristics at High Slip
☐ 40-13	Morrill	Harmonic Theory of Noise in Induction Motors
☐ 40-14	Wynne & Woods	The Application of Traction Motors
☐ 40-15	Noertker	Problems of Electrical Engineering in Transportation
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☐ 40-21	Balsbaugh, Howell & Dotson	Generalized Bridge Network for Dielectric Measurements
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☐ 40-36	Sporn & Gross	Rationalization of System Insulation—III
☐ 40-37	AIEE Committee Report	Proposed Standards for Outdoor Bushings
☐ 40-38	AIEE & EEI-NEMA Joint Report	Recommendations for High-Voltage Testing
☐ 40-39	Clark	The Speedomax Power Level Recorder
☐ 40-40	Faucett, Keener & Helm	The Accuracy of Watt-Hour Meters on Intermittent Loads
☐ 40-41	Goss & Hansen	Rotating Standard for the Measurement of Kilowatt Hours
☐ 40-42	Weller, Trekell & Stebbins	Watt-Hour Meter Performance with Power Rectifiers
☐ 40-44	Bowles, Barrow, Hall, Lewis & Kerr	The Microwave Instrument Landing System
☐ 40-45	Alford & Kandoian	Ultra High Frequency Loop Antennas
☐ 40-47	Diamond, Hinman, Dunmore & Lapham	Upper-Air Weather Surroundings by Radio
☐ 40-48	Loughlin	The Vector Response Indicator
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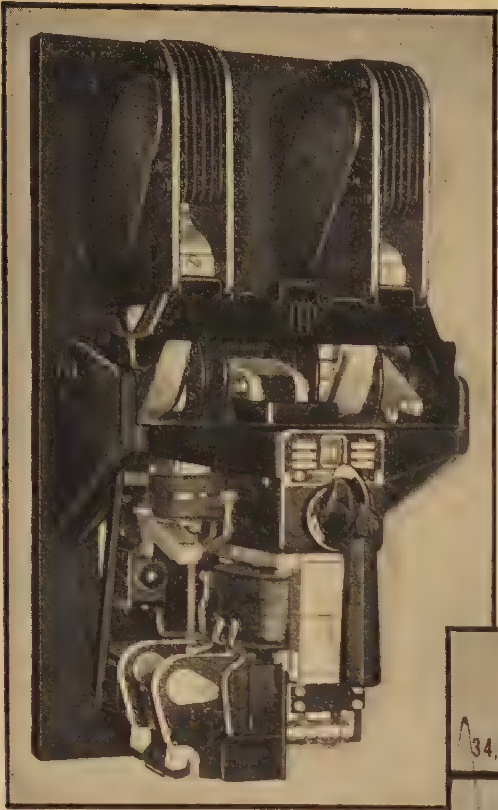

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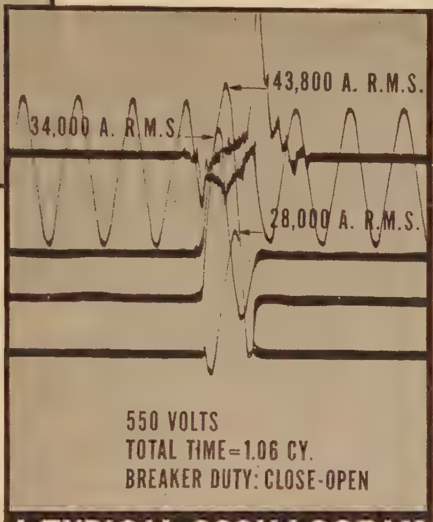

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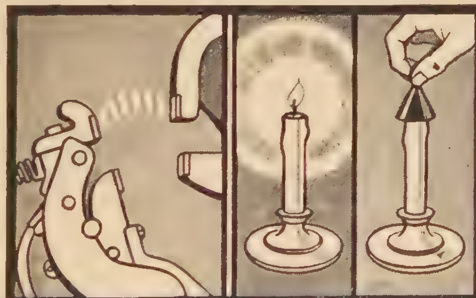
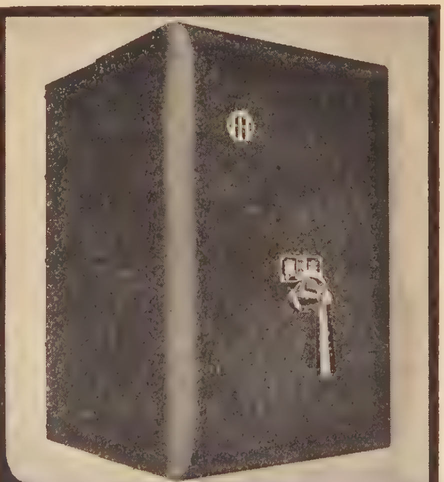


The arc is established and drawn so rapidly . . . and is extinguished so quickly . . .



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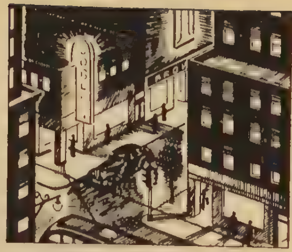
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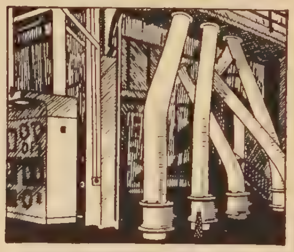
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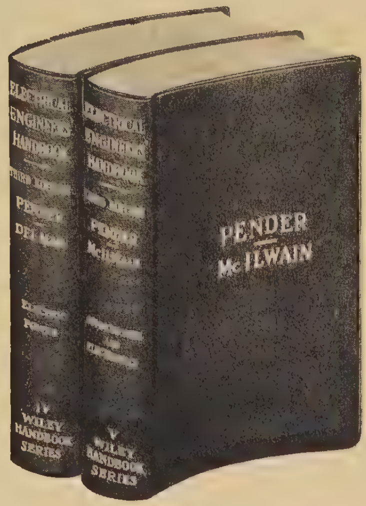

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Transactions

Preprint of Papers and Discussions Comprising Pages 193–256 of the 1940 Volume

Methods of Controlling Radio Interference

C. V. AGGERS
ASSOCIATE AIEE

Synopsis: This paper summarizes the recognized methods for reducing at the source man-made radio noises. The effectiveness of the different controlling methods is discussed in the light of efficiency and utility. The use of shunt-type filters and choke coils is so broad that this paper is confined to the more important applications of these controlling devices. Filter methods are so important that specific applications are discussed in detail. The application of these devices to other apparatus is governed by the type, location, and use of the apparatus.

THE PROBLEM of providing satisfactory radio reception to all areas of the United States requires the co-operation and co-ordination of the various industries involved. Improvements in radio service and reduction of radio noise have been made on many fronts. The solution of the problem lies in the mutual co-operation of interested parties, that is, the broadcasters in providing adequate field strength, the radio set manufacturer in supplying equipment and means for installations with minimum practicable susceptibility to unwanted signals, the radio listener in the proper installation and operation of the set, and the manufacturer and user of electrical equipment to see that it is designed and operated so as to produce the minimum of unwanted stray fields. This paper is limited to the latter subject and gives a few of the experiences of manufacturers in the reduction of radio noise from their electrical apparatus.

Paper 39-145, recommended by the AIEE committees on communication and power transmission and distribution, and presented at the AIEE summer convention, San Francisco, Calif., June 26–30, 1939. Manuscript submitted April 7, 1939; made available for preprinting May 19, 1939; released for final publication October 4, 1939.

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Radio receivers are susceptible to two kinds of noise, natural and man-made. Atmospheric noise, more generally called natural static, creates a problem that rests with the makers of the receiver and to some extent with the number, power, location, and type of broadcasting stations. Man-made radio noise, emanating from rotating electrical machines and stationary electrical apparatus, presents not only a problem to the manufacturers but also to those that apply and use the equipment, as the electrical circuit to which the apparatus is connected may have as much influence on the radio noise as the application of a suitable filter or a change in the design of the apparatus. Fortunately, noise from this type of equipment, unlike natural static, is measurable (although not always easily), and is fairly constant in intensity, for a specific piece of equipment.

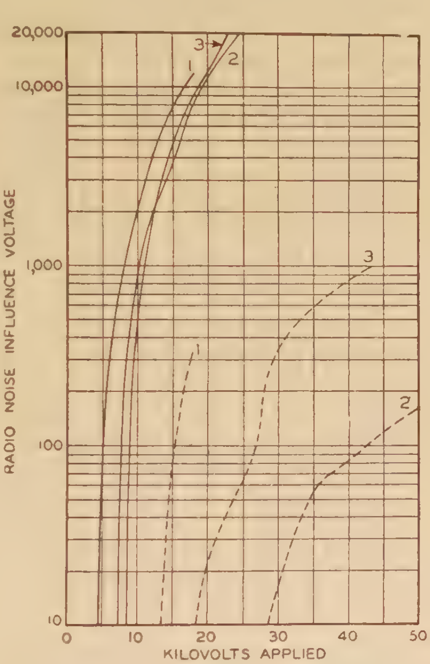


Figure 1. Noise-influence voltage of untreated and treated pin-type insulators

Solid curves—Untreated insulators
Dashed curves—Treated insulators

1—Line voltage 6.9 kv, one piece
2—Line voltage 33.0 kv, one piece
3—Line voltage 33.0 kv, multipart

Both rotating and stationary apparatus are capable of producing radio-noise voltages. The term "radio-noise voltage" will be used hereafter to describe the radio-noise voltage which appears across the input of the radio receiver. This term is used to make a definite distinction between this voltage and the high-frequency voltage measured at the terminals of electrical apparatus when connected to a coupling network. The high-frequency voltage measured at the terminals of electrical apparatus shall hereafter be referred to as the "radio-noise-influence voltage". Commutator and interrupter-type inductor motors are among the rotating apparatus that may produce radio noise while high-voltage line insulators, and to some extent low-voltage porcelain insulators are contributors among non-rotating apparatus.

Methods of Reducing or Eliminating Radio Noise at the Source

Three basic methods of reducing or eliminating apparatus-produced radio noise are recognized and applied with success. They are:

1. Consideration in design
2. Application of low-impedance shunt filters
3. Application of high-impedance series filters

All three methods are not equally effective for a particular device. The method must be suited to the specific source of noise.

Consideration in Design

The possibility of reducing or eliminating the radio-noise-influence voltages in the design of all apparatus is being studied intensively by a large number of manufacturers. All classes of apparatus cannot be economically designed to be noise free but continuous

improvements are being made in many lines. In certain cases the consideration of the noise-influence voltage has resulted in an improvement of the apparatus.

Pin-Type Insulators

In many areas, pin-type insulators on 33- and 66-kv systems are a major source of radio noise on well-designed transmission systems properly constructed and maintained. Radio noise is produced by pin-type insulators as a result of the high voltage gradients across various sections of the insulator. These high voltage gradients are usually across air and other insulation in series. If the gradients are sufficiently high, the air is ionized, allowing a discharge to pass through the air. This discharge is a glow or an arc. In either case, the discharge produces a change in the distributed parameters of the insulator, resulting in the generation of damped transients. It is believed that both ionization and deionization set up damped transients, which appear in connected circuits as noise voltages.

On untreated pin insulators, the principal location of the high voltage gradient is between the line or tie wire and the surface of the insulator. There may also be high voltage gradients across the cement joints between shells, between the pin and the pin hole surface of the porcelain, as well as tangential gradients along the porcelain surfaces of the sheds.

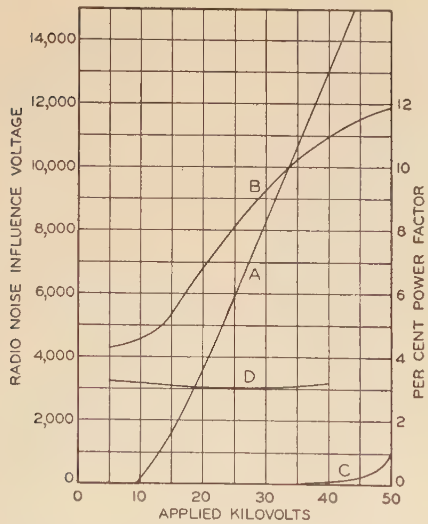


Figure 2. Noise-influence voltage and power-factor of untreated and treated pin-type insulators

A—Noise-influence voltage, untreated insulator
B—Power factor, untreated insulator
C—Noise-influence voltage, treated insulator
D—Power factor, treated insulator

By the proper application of a semiconducting glaze, it is possible to redistribute the voltage to eliminate or reduce the air discharges. The insulators thereupon become free or relatively free of radio-noise voltage as figure 1 shows.

The application of a semiconducting glaze to some pin-type insulators not only reduces the noise-influence voltages but improves the power factor, that is, decreases power loss, as well. The relation between the power factor and the noise-influence voltage of a pin-type insulator is shown by figure 2. The loss, on one of the higher-voltage pin-type insulators, at 40 kv to ground was reduced from 0.98 to 0.38 watt by the application of semiconducting glaze.

Other Porcelain Structures

Studies on a large number of apparatus bushings show that most porcelain structures are free or relatively free of radio noise, at their operating voltage. Occasionally, because of mechanical requirements or space limitations, certain designs of porcelain insulators produce noise voltages. It is on these designs that the proper application of semiconducting glaze can be advantageously applied.

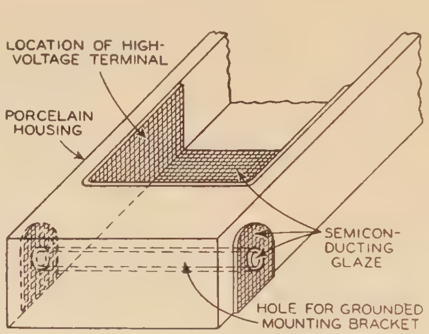


Figure 3. Application of semiconducting glaze to insulating housing

The semiconducting glaze has also been experimentally applied to small porcelain housings, separating outside mounting clamps and inside high-voltage terminals. The proximity of the inside and outside mounting clamps had resulted in high voltage gradients, which produced air discharges at the edges of the clamps along the porcelain surface and between the clamps and the porcelain surface. Upon application of semiconducting glaze to the areas shown in figure 3, the voltage at which noise was detected was increased 100 per cent.

Careful study of insulating structures has indicated that noise voltage can be generated at either the high-voltage or ground terminals or at any intermediate points where the air is overstressed. Partial breakdowns in insulating structures are in general a particularly prolific source of radio noise and can usually be identified by the high values of radio noise accompanying the partial failure.

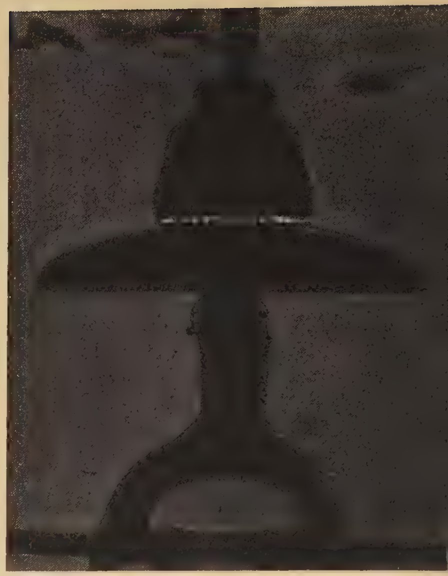


Figure 4A. Visible corona on a ten-inch untreated suspension insulator at 27 kv

Relation Between Corona and Noise-Influence Voltage

Some power companies are now including in their specifications the requirement that apparatus shall produce no visual corona at operating voltage, with the thought that such a requirement defines the radio-noise characteristics. Tests in the laboratory on a number of types of apparatus has indicated that visual corona is not necessarily a true criterion of the noise-influence voltage, because the method used to decrease the stresses in the visible area may, if the proper precautions are not taken, increase the stresses at other locations where the corona cannot be seen.

This can easily be demonstrated by using asphalt emulsion or similar means to reduce the visual corona between the edge of the cap and the porcelain on a suspension-type insulator. The amount of visual corona produced by a ten-inch suspension insulator at 27 kv to ground before and after the insulator had been treated is shown by figures 4*A* and 4*B*. The noise-influence voltages produced by these two insulators were practically the same.

Electrostatic Shielding

Shielding methods are used on some types of equipment. One of the more common applications of this method outside the radio field is the use of

Figure 4B. The ten-inch treated suspension insulator shows no corona at 27 kv

shielding in ignition transformers for oil burners where the spark discharge on the secondary side produces a radio-noise voltage on the primary supply line through the mutual coupling between the primary and secondary windings. The application of shielding does not provide as great a reduction in noise as an external capacitor filter. However, with this type of transformer the application of shielding is more economical than a capacitor filter.

Shielding cannot be applied satisfactorily to all types of transformers because a low-impedance high-frequency ground is difficult to obtain in the general application of this type of equipment. Experiments and limited application indicate that shielding will find application in eliminating unwanted radiation from various other equipment.

Low-Impedance Shunt Filters

Some apparatus is so constructed that it is impossible to reduce the noise-influence voltage to a satisfactory level through design changes. The application and location of such apparatus will determine whether a filter will be required. The low-impedance shunt filter is generally found to be the most satisfactory for low-voltage applications. Low-impedance shunt filters are simply capacitors of a proper size and rating, suitably connected to reduce the line-to-line and line-to-ground noise-influence voltages. This type of filter finds wide application on commutating machines, and make-and-break devices of various kinds.

The commutating motor produces a noise-influence voltage that has two components that must be separately considered from an interference standpoint. One voltage component is produced between the terminals of the machine, and is commonly referred to as the line-to-line noise-influence voltage. The other voltage component appears between the supply lines jointly as one terminal and ground as the other, and is called the line-to-ground noise-influence voltage.

The noise-influence voltage produced by a commutating machine, is propagated along the supply lines and induces a noise in the radio-receiver antenna by mutual coupling. In general, very little radio-noise voltage is induced in the radio antenna by direct radiation because the field strength around a motor decreases rapidly with increased distance from the machine. The field strength ten feet from a one-fourth-horsepower motor will usually be less than one microvolt per meter.

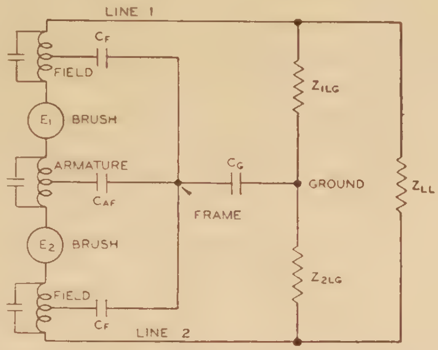


Figure 5. Equivalent circuit of a commutating machine as an interference generator

C_F—Capacity of field to frame
C_{AF}—Capacity of armature to frame
C_G—Capacity of frame to ground
Z_{1LG} and Z_{2LG}—Line-to-ground impedances
Z_{LL}—Line-to-line impedance

An analysis of the equivalent circuit of a commutating machine as an interference generator, figure 5, shows that the voltage from each line to ground, the voltage between lines, and the voltage from frame to ground will be zero if the impedance of each line to the frame of the machine is made zero.

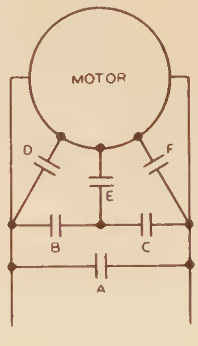
If the impedance of the lines to ground are balanced ($Z_{1LG}=Z_{2LG}$) the voltage from line to ground and frame to ground will not be greatly affected if the line-to-line impedance is made zero. Usually this impedance is not balanced, and some reduction in the line-to-ground voltage is obtained when the line-to-line impedance is decreased. This decrease is insufficient to give adequate noise reduction in most cases. The frame-to-ground voltage is practically unaffected by a reduction in line-to-line impedance under unbalanced line-to-ground impedance conditions.

The closest approach to the ideal condition of zero line-to-frame impedance is obtained with a properly designed shunt capacitance filter. These capacitance filters can be designed to give a minimum impedance over a definite frequency band. Such a filter, designed for one wave band will be less effective in other bands. If maximum protection is desired over a wide frequency band, a number of capacitance filters must be used.

In the United States the filters are nominally designed to give the maximum noise reduction over the broadcast band, which extends from 550 to 1,500 kilocycles. Some apparatus for use elsewhere, however, must be designed to give maximum noise reduction also over the 250 to 400 kilocycle band. Suitable noise reduction in this low-frequency range usually requires larger capacitors for proper filtering.

Commutating motors can be operated either with the frame grounded or ungrounded. When the frame is grounded, maximum noise reduction is obtained by placing capacitors from each line to the frame. The reduction of the noise-influence voltage from a $^1/_{15}$-horsepower motor using two 2.0-, 0.5-, and 0.1- microfarad capacitors over the frequency range 150 to 2,500 kilocycles is shown in table I. The capacitors were connected at *D* and *F*, figure 6, with a total lead length of five inches. The 2.0-microfarad capacitor gives maximum protection in the lower frequency band. The 0.5- and 0.1-microfarad capacitors produce as great a reduction of noise at 1,000 kilocycles and above as does the 2.0-microfarad capacitor. The length of leads used on capacitance filters is important because the lead inductance will tune the ca-

Figure 6. Composite figure showing connection of filter capacitors in vee, wye, and delta



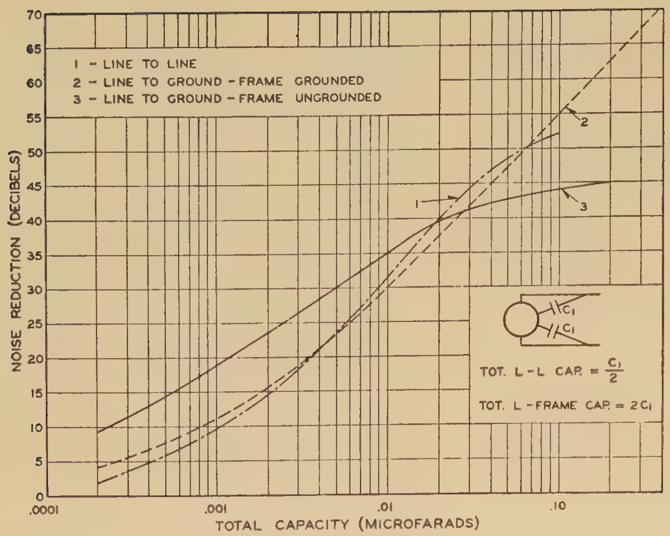


Figure 7. Noise-reduction ratios as a function of total filter capacitance

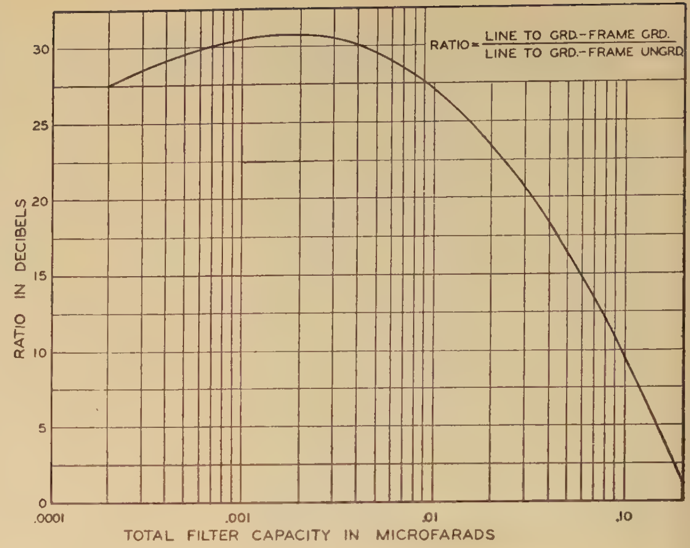


Figure 8. Ratio of line-to-ground noise with the motor frame grounded to the line-to-ground noise with the frame ungrounded as a function of the total filter capacitance

pacitance to series resonance and provide minimum impedance and maximum noise reduction at a definite frequency.

Filters for Ungrounded Device

High-capacitance filters can be used only on grounded-frame machines. Low-capacitance filters to reduce the radio-influence voltage of ungrounded devices such as vacuum sweepers and food mixers must be used to prevent unpleasant shock when they are touched.

If the frame of an unfiltered motor is ungrounded the frame will float at a potential somewhat above ground, depending on the capacity of the windings to the frame and the frame to ground. If the frame is touched no shock will be noticed because of the small capacitance of the windings to the frame. However, when the same motor is filtered, a capacitor is usually connected from the line to the frame. This capacitor has many times the capacitance of the windings to the frame so if the frame is touched, sufficient charging current of the filter capacitor may flow through the body to ground to cause an unpleasant shock.

The Joint Co-ordination Committee on Radio Reception of Edison Electric Institute, National Electrical Manufacturers Association, and Radio Manufacturers Association has recommended that the current to frame of capacitance-type filters be held below 0.3 milliampere. Therefore a filter for an ungrounded device must be designed to give maximum reduction of noise-influence voltage with a limited amount of capacitance.

To show the effects of various size capacitors in filters used for suppressing noise-influence voltages, tests were made on a 1/16-horsepower commutating motor. Measurements were made in accordance with the recommended practices of the Joint Co-ordination Committee on Radio Reception. The filter capacitors were connected three ways; in vee, one capacitor from each line to the frame; in wye, two capacitors across the lines, one capacitor from the midpoint to the frame; and in delta, one capacitor between the lines and a capacitor from each line to the frame. Table II shows the average noise reduction ratios, expressed in decibels, for the different filter combinations.

The relation between total capacitance and noise reduction expressed in decibels is shown in figure 7. The abscissa values are in terms of total capacitance line-to-frame or line-to-line and are used with the proper noise-reduction curves. As an example, assume a filter combination of a 0.01-microfarad capacitor connected from each line to the frame. The line-to-line capacitance would be 0.01/2 or 0.005 microfarad and the line-to-frame capacitance would be 2×0.01 or 0.02 microfarad. The 0.005 figure would be used in referring to the line-to-line curve and the 0.02 figure to the line-to-frame curve.

These curves show that with the motor frame ungrounded, little improvement in line-to-ground noise is gained by increasing the capacitance of the line-to-frame capacitor beyond 0.02 microfarad. In general this value will vary with the stray capacitance of the motor to ground as well as the size and type. For the line-to-line and line-to-ground condition with the frame grounded, the improvement increases with increase in capacitor size.

The ratio of line-to-ground noise with the motor frame grounded and ungrounded for various sizes of capacitors is shown in figure 8. To reduce the number of measurements only the vee filter connection was used. The data

Table I. Effect of Capacitor Size in Reducing Radio Noise From 1/15-Horsepower Motor

Type of Measurement	Capacitor C_1 (Microfarads)	Reduction of Radio-Noise Output (Decibels)* 200 Kc	340 Kc	600 Kc	1,000 Kc	1,400 Kc	2,000 Kc	2,500 Kc
Line-line	0.1	29.7	33.9	40.5	45.9	41.4	46.7	41.7
	0.5	43.6	49.6	64.8	50.7	39.2	41.8	40.0
	2.0	60.1	54.8	54.8	48.6	38.7	41.2	39.2
Line-ground, frame ungrounded	0.1	36.8	44.0	41.6	37.9	27.2	38.1	37.4
	0.5	41.2	46.7	41.0	37.9	30.4	37.6	37.4
	2.0	40.6	45.2	42.1	39.1	33.5	39.9	39.1
Line-ground, frame grounded	0.1	40.5	47.0	53.0	55.0	44.8	44.8	39.8
	0.5	56.0	62.0	60.6	44.6	43.4	53.4	40.9
	2.0	65.7	77.2	73.7	49.8	49.8	49.2	49.3

$$* = 20 \log \frac{\text{(radio-noise voltage unfiltered)}}{\text{(radio-noise voltage filtered)}}$$

Table II

Test	A	B	C	D	E	F	Maximum Filter Current at 120 Volts, 60 Cycles (Milliamperes)	Average Noise Ratio in Decibels, Unfiltered to Filtered: Line-Ground (Grounded)	Line-Ground (Ungrounded)	Line-Line*
1	0.05						0	0	0	46.9
2				0.0001		0.0001	0.005	4.6	9.8	0
3				0.0005		0.0005	0.023	11.4	19.4	3
4				0.001		0.001	0.045	15.7	24	6.7
5				0.003		0.003	0.135	24.4	31.2	12.7
6				0.006		0.006	0.27	32.6	36.2	16.8
7				0.01		0.01	0.45	37	40	24.2
8				0.05		0.05	2.25	55.7	44	43
9				0.10		0.10	4.5	63	45	48.5
10				0.2		0.2	9	69.1	40	52.2
11	0.05			0.003		0.003	0.27	26	31.2	46
12	0.05			0.006		0.006	0.54	32	37.1	46.8
13	0.05			0.01		0.01	0.91	36.5	40	46.8
14	0.01			0.003		0.003	0.27	25.7	31.2	33.3
15	0.01			0.006		0.006	0.54	31.7	37.1	33.3
16		0.01	0.01		0.006		0.21	23	29.4	26.7
17		0.01	0.01		0.01		0.30	27.7	32.7	26.4
18		0.10	0.10		0.003		0.13	17.8	25.4	46.2
19		0.10	0.10		0.006		0.26	24.8	31.2	46.2
20		0.10	0.10		0.01		0.43	51.4	41.5	46.2

* There was no substantial change in the line-line noise with frame grounded or ungrounded.

shows that for the smaller sizes of filter capacitors the radio-noise voltage to ground is increased by grounding the frame while for the larger sizes of capacitors, the noise voltage is decreased by grounding the frame.

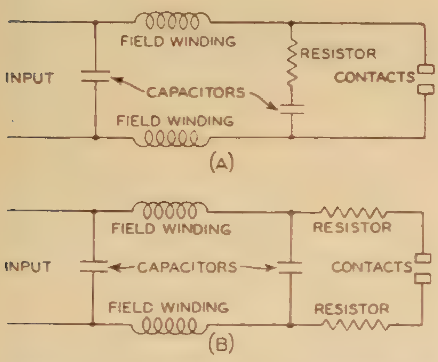


Figure 9. Filter circuits for interrupter-type inductor motors

Figure 10. Noise measurement along a 66-kv transmission line showing the effect of reflections

It should be noted that these data indicate results on a particular motor and while it is indicative of the performance of commutating motors, the conclusions should not be generally applied to all apparatus.

Make-and-Break Contacts

Apparatus in which electrical contact is made and broken frequently is the source of an annoying form of interference. Make-and-break circuits are usually filtered with a resistance and capacitance combination. The amount of capacitance across the contacts is important from the standpoint of life of the contacts and the reduction of noise-influence voltage. The resistance properly placed in the circuit, performs two functions; it limits the short-circuit current of the capacitor, and it acts as an internal impedance in the noise-voltage circuit. A combination of capacitance and resistance can usually be chosen to achieve the desired noise reduction.

The interrupter-type motor is an example of this form of noise generator. This motor depends for its operation on a properly synchronized make and break of the current flowing in the field coils.

Capacitance is usually connected across the make and break contacts of the motor to reduce arcing and heating of the contacts. This capacitance must be kept sufficiently low that the contacts will not weld and cause sticking when the capacitance is short-circuited by the contacts. The capacitance that is generally used for this purpose is not sufficient to reduce the noise value to a satisfactory level. The application of larger capacitance requires the addition of resistance to reduce the capacitor discharge when the contacts close. Two resistance and capacitance combinations which are satisfactory for this type of application are shown by figure 9. The combination shown by figure 9*B* has been used to reduce the noise voltage of an electric razor to less than 0.5 per cent of its original value.

The circuit shown by figure 9*A* does not give the reduction of figure 9*B* on this type of make-and-break circuit, but is applicable where resistance cannot be placed in series with the line.

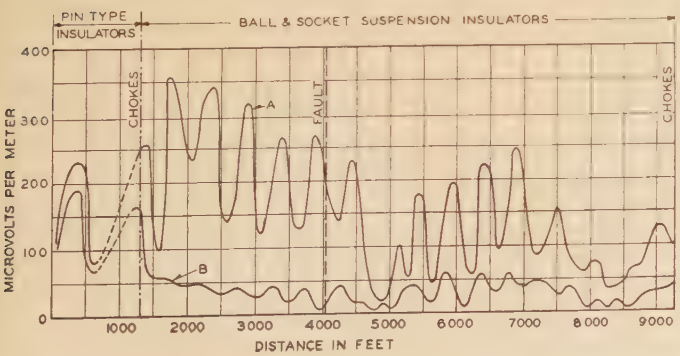
High-Impedance Filters

Radio-Frequency Choke Coils

When high-voltage apparatus is considered, the cost of shunt-type filters becomes uneconomical and high-impedance series filters must be applied. These filters take the form of tuned choke coils and find application on high-voltage transmission lines, telephone lines, and distribution networks. They are not usually used to reduce radio

Figure 11. Noise measurements along a 66-kv transmission line showing the effect of parallel lines

A—Line normal
B—Telephone choke short-circuited
C—Line dead at pole 5-39



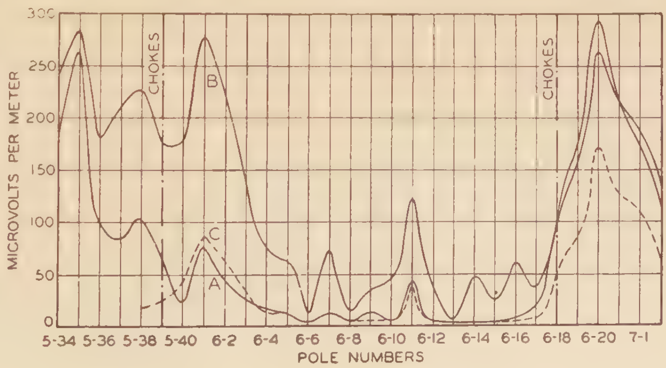


Table III

Test Number	Description of Tests	Noise Starting Voltage (Kilovolts)
1	Standard 6.9-kv insulator on wood cross arm with wood pin	19.8
2	Standard 6.9-kv insulator on wood cross arm with metal pin. Pin not grounded	7.7
3	Standard 6.9-kv insulator on wood cross arm with metal pin. Pin grounded	4.9
4	Standard 6.9-kv insulator on metal pole-top pin. Pin not grounded. Guy-wire hook and lag bolt close to pin grounded	5.6
5	Standard 6.9-kv insulator on metal pole-top pin. Pin not grounded. Grounded guy-wire hook and lag bolt removed	5.75
6	Standard 6.9-kv insulator on metal pole-top pin. Pin grounded	4.9
7	Treated 6.9-kv insulator on pole-top pin. Pin not grounded. Guy-wire hook and lag bolt close to pin grounded	21.3
8	Treated 6.9-kv insulator on wood cross arm with metal pin. Pin not grounded	13.8
9	Treated 6.9-kv insulator on wood cross arm with metal pin. Pin grounded	20.25
10	Treated 6.9-kv insulator on wood cross arm with cross arm brace grounded. Pin not grounded	10.75

noise at the source but are used to attenuate the transmission of noise from specific sections of the circuit.

Field experience has demonstrated the radio-frequency choke coils can be applied to transmission lines and give satisfactory performance provided they are applied properly. One of the most common mistakes made in their application is attempting to sectionalize a part of a line without completely eliminating the radio noise in the section. When noise is generated in the sectionalized part of the line, the radio-frequency noise is reflected at the choke coils. This noise may be amplified a number of times, depending upon the distance between the chokes.

An example of such a situation is illustrated by figure 10 curve *B* indicates the noise field strength measured along a reinsulated section of a 66-kv pin-type transmission line. The section was reinsulated with suspension insulators. Choke coils were installed at each end of the reinsulated section.

After the line had been in service for several years, a line fault occurred which resulted in numerous radio complaints. The line was again surveyed and field strengths as shown by curve *A*, figure 10, were obtained. Normally a high noise level is obtained at the pole where the fault occurs, however, it may be seen by referring to curve *A*, that noise peaks occurred all along the major portion of the reinsulated section. Several unsuccessful attempts were made in an effort to locate the fault. As a last resort, the chokes were short-circuited and the fault was readily located at the point indicated on figure 10. After the fault had been corrected, the choke coils were again inserted in the line and the noise returned to its original level.

It should be noted that the noise peaks occur approximately every 450 feet, which is a half wave length of 1,090 kilocycles. This is exactly the frequency of measurement indicating reflections from the choke coils.

This same effect is obtained when a reinsulated section is not entirely free of radio noise. A number of radio-frequency choke-coil installations have been declared unsuccessful due to insufficient reduction of noise. These unsatisfactory choke-coil installations have in general been caused by the lack of proper reinsulation in the desired sections. If reflections are present in an apparently unsuccessful choke-coil application, a complete inspection of the reinsulated section should be made.

The proper application of radio-frequency choke coils requires that they be inserted in all parallel lines. The radio-noise field strength produced by a 66-kv line with a paralleling telephone line on the same poles, after it had been reinsulated and choke coils inserted in both the 66-kv line and telephone line, is shown by curve *A* of figure 11.

During a storm one of the telephone choke coils was destroyed by lightning and a resurvey of the line indicated a noise level as shown by curve *B*. After the insertion of a new telephone choke coil, the noise level again was reduced to that shown by curve *A*. The noise level of this line when the line was open at pole 5-39 and energized from the other end is shown by curve *C*.

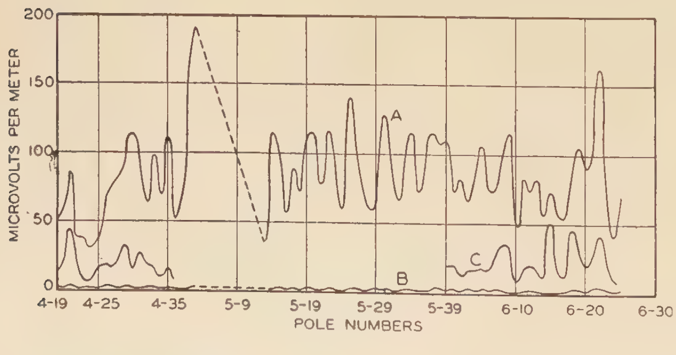


Figure 12. Noise measurements along a 66-kv transmission line showing the effect of applying asphalt emulsion to pin-type insulators

Field Investigations of Noise From Transmission-Line Equipment

In certain areas an important source of radio interference produced by electric-power-system apparatus is from high-voltage transmission lines. In general its importance arises not so much from its severity as from the fact that it may be continuously present. The situation is aggravated by the fact that such equipment is located in areas of low broadcasting field strengths.

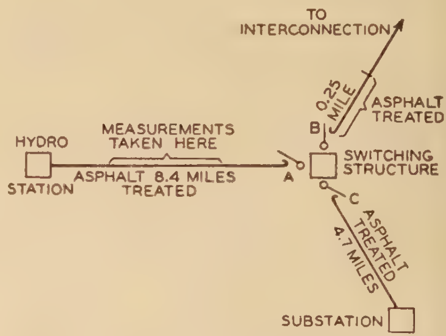


Figure 13. Schematic switch diagram of the 66-kv transmission line of figure 12

Less complaints would arise from the use of this equipment if the field strengths that are available during evening and night hours, were available during the day. Usually the daytime field strengths are from one to ten per cent of the evening and night field strengths, and as a result complaints are received even with low levels of radio-noise voltage.

Radio noise from high-voltage systems can be caused by defective apparatus; poorly spliced, nicked, or small-size conductors; improperly designed hardware; hardware installed without sufficient clearance; arcing horns; improperly inserted cotter pins, and many other less obvious details. Radio noise can be produced by the high-voltage system apparatus in the performance of its normal duty and must be eliminated by design after the cause is detected. At substations, radio noise is usually pro-

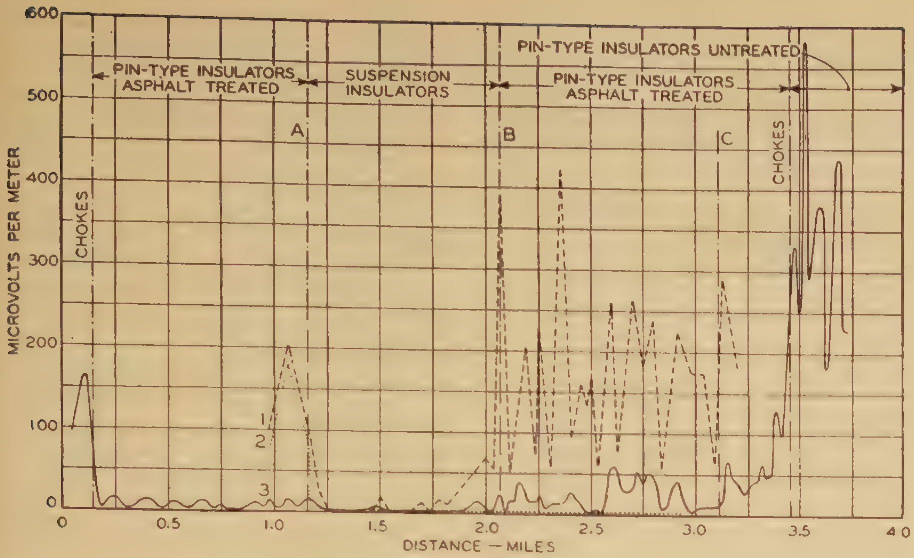


Figure 14. Noise measurements along a 66-kv transmission line with different types of reinsulation

duced by certain types of apparatus whose limitations in this respect must be recognized and allowed for.

Rural Lines

It is generally believed that insulators on 11.8-kv rural transmission lines do not produce radio interference. Where wood pins are used this is usually true. However, if metal pins are used with standard insulators, there is considerable possibility of radio interference. A number of such cases have been investigated and one in particular where a power company had changed from a cross-arm construction to a pole-top construction. After the change had been completed, this line, previously interference free, became the cause of many radio complaints.

To check this condition, a pole which had been standing in the open for several years, was brought into the laboratory and arranged so that the cross arm, pole-top pin, guy-wire hook, and lag bolts were mounted exactly according to the public-utilities specifications. The results of these tests are shown in table III.

The insulator on the wooden pin did not create any noise below 19.8 kv. This same insulator with a grounded metal pin started to create noise at 4.9 kv, as measured by the circuit adopted by the joint co-ordination committee of EEI, NEMA, and RMA on radio reception. This insulator mounted on the pole-top pin started to produce noise at 5.6 kv. With the guy-wire hook and lag bolt removed from the pole, this insulator still started to produce noise at 5.75 kv.

Tests 8, 9, and 10 are interesting because they show that under actual field conditions the starting noise voltage can be lower when the pin is ungrounded, because of the leakage current flowing from the metal pin to the cross arm or from the cross arm to a grounded cross-arm brace.

Test 7, indicated that it would be necessary to use radio-interference-proof insulator on the pole-top pin if interference was to be eliminated. This procedure was adopted by one power company. Another company transferred to a wooden pin mounted on a metal bracket.

Application of Asphalt Emulsion

Asphalt emulsion has been used successfully in many applications to reduce the radio noise produced by high-voltage pin-type insulators. The effect of such an application on an actual line is shown by figure 12. The treated line, switching stations, and the point where the measurements were made are schematically shown in figure 13. Curve *A* of figure 12 shows the noise level of a section of this line before application of the asphalt emulsion with all switches indicated in figure 13 closed. Curve *B*, figure 12, shows the noise level of the same section after the application of asphalt emulsion and switch *C*, figure 13, open. Curve *C*, figure 12 shows the noise level along parts of this section after the application of asphalt emulsion and switch *C*, figure 13, closed. Considerable radio noise is shown coming from the untreated section. Also, figure 12 shows that the noise is not attenuated as rapidly as is frequently assumed because the measurement made at pole 4-19 is approximately five miles from switch *C*. Choke coils should be inserted between switch *C* and the untreated section for maximum effectiveness.

The reduction in radio noise from another line with the application of asphalt emulsion is shown in figure 14. This line was a 66-kv pin-type transmission line mounted on wood poles.

The first attempt at reducing the radio noise along a section of this line consisted of reinsulating the section between *A* and *B* with suspension insulators, treating the pin-type insulators from point *B* to point *C* with asphalt emulsion, and inserting radio-frequency choke coils at *A* and *B*. The noise along this line with this construction is shown by curve 1, figure 14.

This installation did not protect sufficient area and tests were conducted to determine the noise level of asphalt-treated section by cutting the line at point *C* and energizing the line from the other end. The noise level under the asphalt-treated section (*B* to *C*) then became very low, as indicated by curve 2, figure 14.

The line was reinsulated as shown by figure 14, and the choke coils moved to their final position as shown. The noise level over the entire area is shown by curve 3, figure 16.

The results shown by these curves demonstrate that:

1. Asphalt emulsion, when properly applied, is fairly effective in reducing inherent pin-type insulator noise.
2. Suspension insulators provide the lowest noise level.
3. Radio noise travels for a considerable distance along the line conductors making the use of radio-frequency choke coils necessary in order to avoid the replacement or treatment of an excessive number of insulators.

Discussion

Charles J. Miller, Jr. (The Ohio Brass Company, Barberton): Mr. Aggers has summarized quite clearly some of the principles that may be applied to control radio interference.

In connection with the application of a semiconducting glaze to pin-type insulators he states that its use improves the power factor of the insulator. He gives no explanation as to why the losses are reduced. In the case of the ordinary insulator, the corona discharge at the tie wire and conductor, and at other parts of the insulator if it exists, requires a small but definite amount of energy to produce it. This represents an energy loss in excess of that occurring within the porcelain itself. With

the application of a semiconducting glaze which effectively suppresses the formation of corona, the total losses of the insulator are reduced and accordingly the power factor is improved.

The electrostatic capacitance of the treated unit is usually somewhat greater than that of an untreated unit, and if the inherent losses in the porcelain are equal in each insulator, the power factor of the treated unit will be smaller than that of the untreated unit. However, it is probably the suppression of the corona discharge that contributes the greater share to the lower power factor of the treated insulator.

The comments on the relation between corona and noise-influence voltage are very interesting and confirm many similar observations made at the Barberton laboratory of the Ohio Brass Company. For example, tests on three-unit strings of suspension insulators have shown wide variations between the visual corona point and the radio-influence voltages. On two similar strings the lowest visual corona point detectable corresponded to a radio influence voltage of 5 microvolts in one case and 50 microvolts in the other.

The use of radio-frequency choke coils in connection with high-voltage transmission lines to isolate or block out the interference from a given protected area is a well-known principle. The use of tuned choke coils in series with every conductor at the point of installation will provide a very effective blockade for a given band of frequencies centered on the resonant frequency of the choke. It has been customary to tune these coils at a frequency somewhere near the middle of the broadcast band. In special cases the coils may be tuned to suppress any particular band of frequencies. However, the use of all-wave receivers now makes it desirable to provide wide-band suppression. A statement of how wide a band of frequencies may be satisfactorily suppressed by the use of tuned choke coils and what provisions could be made for wide-band suppression would be appreciated.

The application of asphalt emulsion for the suppression of radio noise from pin-type insulators has been used for a number of years. However, it is generally conceded that the treatment is not permanent as it tends to deteriorate after a few years. It would be interesting to know the life of the asphalt treatment on the transmission lines discussed by Mr. Aggers in this paper.

W. F. Grimes (Radio Interference Engineering Bureau, Inc., Los Angeles, Calif.): C. V. Aggers in his paper presents a number of methods for controlling radio noise originating under specified conditions. The suppression methods described have all demonstrated their efficiency under actual operating conditions and they are in everyday use. The title of the paper has been well chosen, suggesting as it does additions to existing equipment for the sole purpose of improving radio reception.

It may be of interest to consider, briefly, the conditions under which controlling methods must be applied and the relation of these conditions to other circumstances under which the radio listener has been found to be not satisfied with radio reception. The data to be considered are based on the experience of the co-operative radio-interference investigating agency which is operating in and near the city of Los Angeles, in an area of comparatively high broadcast field strengths. The investigations made by this agency may be divided into four groups which represent separate responsibilities for investigation. Forty-eight per cent of the investigations are traceable to one or more defects in the listener's installation or receiver; 24 per cent, either too intermittent to trace or cleared before the source determined; 20 per cent, electrical apparatus or appliances, exclusive of electric-utility apparatus; 8 per cent, electric-utility apparatus.

Those sources of interference to which controlling methods should or may be applied represent less than 20 per cent of the total investigated. Of this number a majority require servicing or replacement rather than the addition of filters or other suppression equipment. Worn and burned contacts, loose connections, broken bushings, and similar sources of interference should be repaired or replaced.

Nearly 50 per cent of the radio listeners who report interference do so because they lack understanding of the problem or have not been properly advised. These individuals believe their trouble is due to interference when actually it is due to a defective receiver or lack of correct receiver installation.

These remarks are intended only to point out that in order to develop maximum use of radio-receiving equipment it is necessary to consider all of the factors disturbing to the listener. Methods of controlling radio interference must eventually be applied to apparatus, when required, at the point of manufacture. The radio and electrical industries are urged to consider the general problems of the listener and to initiate an active co-operative campaign designed to develop listener interest and understanding.

A. M. Lane (representing General Electric Supply Corporation and Locke Insulator Corporation, San Francisco, Calif.): Mr. Aggers has presented a very interesting paper. These remarks are with reference to that part of his paper dealing with radio-frequency choke coils and are somewhat supplementary. Possibly a brief description of radio-frequency attenuation coils for wire lines would be of interest.

Radio noise caused at any point on a power system travels along the wires with very little attenuation, thus producing interference for many miles. To prevent all interference at a certain location, it has been necessary in the past to clear up all noise sources for many miles in all directions along the wires. Experience has shown this to be extremely difficult and expensive, and the job is never finished because new sources of noise are continually forming.

Fortunately, radio noise is objectionable only at certain sections of most power lines, such as in thickly settled districts or near radio-receiving stations. In the course of our investigations we found that the Radio Interference Specialty Company had developed a practical method which prevents radio noise of all frequencies from passing a given point in a power line. Thus, a section of line where noise is objectionable can be isolated from the rest of the power system with regard to radio-frequency noise and at the same time not interfere with the power service, or the transmission of carrier frequencies. These isolated sections can then be economically freed from noise sources, and the noise problem is thus eliminated permanently.

The isolation of sections of power lines from radio noise is accomplished by the use of very small inductance coils properly spaced along the line at each end of the section to be isolated. Two of these coils in series in each power wire constitute an attenuation section and reduce the noise level approximately 25 decibels. Two sections of attenuation consist of three coils in series, the center coil being larger than the end coils. This arrangement gives approximately 50 decibels noise attenuation. The 60-cycle loss for two such sections is approximately equal to 1,200 feet of line.

In practice, it has been found that the reflections at the coils are so low that sources of local trouble within the protected area may be readily located.

The spacing between coils is important and depends upon the electrical constants of the power line and the lowest frequency it is desired to stop. However, the spacing can always be arranged so that the coils can be mounted on existing poles. The coils should always be installed where there are the least number of paralleling wires such as telephone lines and secondaries, as these lines pick up and carry the radio noise. All coils are fitted with spark gaps as a protection against lightning and have been tested with artificial lightning of 2,000,000 volts.

Attenuation coils meeting the requirements of the telephone and telegraph companies have been developed for installation on open-wire lines, even though such lines must accommodate telephone and telegraph carrier channels.

One of the earliest of the many existing installations was made for the protection of the radio-receiving station of the Mackay Radio Telegraph Company located about 40 miles south of San Francisco near the ocean. In this installation coils were placed in the 11-kv power wires and the telephone toll wires. This installation has thoroughly protected all frequencies for the radio company's world-wide receivers since the first part of 1933.

Measurements of the amount of reduction in interference have been made by the telephone company and several power companies. These measurements show that a reduction of 98 per cent in the radio noise may be obtained over the frequency band from 500 kilocycles to 14 megacycles. It is probable that the protection extends to much higher frequencies, although no such measurements have yet been made.

R. J. Sullivan (Commonwealth and Southern Corporation, Jackson, Mich.): This paper is a valuable contribution to the literature on the subject of radio interference. This is a field of investigation in which much remains to be accomplished, and in which a comparatively small amount of published information is available. No doubt many independent investigations have been carried on, the results of which have not been published, perhaps partly because more or less makeshift apparatus was used which did not permit the results to be published in the quantitative form

of curves and tabulations which are usually considered to be requisites of successful technical papers. This situation will be improved if the standard test circuit recommended by the Joint Co-ordination Committee on Radio Reception becomes widely used in such investigations.

The section of the paper dealing with radio interference produced by electric-power-system apparatus invites further discussion. The statement that radio noise produced by high-voltage system apparatus ". . . must be eliminated by design after the cause is detected", is part of the story; and the statement that "radio noise from high-voltage systems can be caused by defective apparatus," is another part. Improvements in design will not eliminate individual cases of interference due to defective materials or poor workmanship. In either case if the noise-radiating equipment is allowed to get into service it may cause considerable irritation and expense to its purchaser before being identified as a source of radio interference. This paper offers useful information on dealing with equipment already in service, but it would be very interesting to know what is being done by the manufacturers in the way of production testing of equipment for radio interference before it leaves the factory. This would be considered as an important part of the test procedure by those members of the operating organizations who have the job of investigating radio-interference complaints.

It is not clear what is meant by "high-voltage systems". Severe interference can be caused by defective distribution apparatus of voltages at least as low as 6,900 volts. Interference has been found to originate in distribution transformers in the high-voltage bushings, high-voltage leads and taps which are not spaced sufficiently, defective insulation which would withstand the usual high-potential insulation tests, and other defects, such as carbonized terminal blocks. One investigation disclosed a batch of new 7,200-volt distribution transformers which caused a very high level of radio interference due to the fact that they had been overbaked during the impregnation process at the factory which raised blisters in the insulation between the high-voltage and low-voltage windings. The potential gradient across the insulation produced a glow discharge in these voids which started at less than half rated voltage. The overbaking also left the insulation in a brittle condition, but the defect was only detected by the radio-interference test, which could have served the same purpose during a factory test.

A considerable range of starting voltages for radio interference has been found for transformer bushings filled with asphalt compounds, above 7,200 volts, due to voids in the compound. This characteristic is subject to control in the manufacturing process if it is taken into consideration. Many of the offending bushings are old types, of which large numbers are still in service and still being manufactured for replacements.

In connection with the treatment of insulators to reduce radio noise, a discussion of the following points should be of interest:

What variations can be expected in the radio-interference starting voltages of a number of semi-conducting glaze insulators of the same design with respect to rated voltage?

What effect does dirt have on the radio-interference qualities of treated insulators?

How long can asphalt emulsion be expected to act as a radio-noise-reducing agent when exposed to normal weather conditions?

C. V. Aggers: Mr. Lane has presented a very interesting discussion on the radio-frequency attenuation coils which have been used to isolate sections of telephone and power lines. These coils are apparently designed so as to provide a single- or two-section T-type low-pass filter in which the capacity of the conductors to ground is used as the capacitance element of the filter.

This method of isolation should, and apparently does provide adequate protection over a very wide frequency range provided the precautions enumerated by Mr. Lane are adhered to.

Mr. Miller has explained why the losses are reduced by the application of semi-conducting glazes. However, if the proper precautions are not taken, it is possible to increase the inherent loss of an insulator to such a value that these losses may exceed the reduction obtained by the elimination of the corona discharges.

Mr. Miller pointed out that the use of all-wave receivers now makes it desirable to provide wide-band suppression. In general, the present type of chokes are designed to provide protection in the broadcast band, 550 to 1,500 kilocycles. Choke coils to provide protection over a wider band have not, in general, been found necessary up to the present time. If and when wider-band-spread protection is desired, the method discussed by Mr. Lane will probably offer the most economical solution.

Chokes for other applications have been designed for wider band spreads. One application required a coil that had a minimum impedance of 10,000 ohms from 300 to 3,000 kilocycles.

Mr. Miller requested the life of the asphalt treatment on the transmission lines discussed. These lines were inspected by the power company after approximately five years of service and it was felt, at that time, that they could reasonably expect a life of ten years from this treatment. The life of this treatment, of course, varies with the precautions taken during its application as well as the climatic conditions.

Mr. Sullivan desires to know what is being done by manufacturers in the production testing of equipment radio interference before it leaves the factory. At least one company is testing all treated insulators before shipment. Other companies are considering the same procedure. In general, radio interference is considered in the development of the certain type of equipment and tests conducted on the first production lots. If these units are satisfactory then sample lots are checked at various intervals.

It is realized that severe interference can be produced by 6,900-volt equipment. In general, the term high-voltage systems has been applied to voltages above 1,000 volts in order to distinguish this equipment for the equipment that operates from the distribution secondaries.

Referring to Mr. Sullivan's question regarding the variation that can be expected in the ratio-interference starting voltage of a number of semiconducting-glaze insulators of the same design, no one has been able definitely to define starting voltage. We have not attacked the problem from this angle because some insulators produce a measurable amount of noise voltage at what you might call its starting voltage. On other insulators the voltage may vary five to ten kilovolts between the point of first detection of noise by a headset and the point where the unit produces a measurable value (in the order of 10 or 20 microvolts). However, if a definite number of microvolts is used to define the starting voltage, there may be considerable variation in the starting voltage. This variation will depend upon the type of treatment used on the insulator and the method of applying the test voltage.

The general method of attack has been to measure the noise at various voltages and plot an envelope curve. This curve gives the variation which can be expected in any one design and the maximum value must be below any noise voltage which may be considered for standardization.

The type of data described above is for use only by the design engineer as the operating engineer is only interested in the noise voltage at the operating voltage which after all is the criterion as to whether an insulator will be a cause of radio-interference complaint.

The insulator manufacturers in general are attempting to establish a definite number of microvolts for a particular voltage classification. The values which they are considering are sufficiently low to prohibit any possibility of a noise complaint from this equipment.

Experience in the field to date has indicated that dirt has little or no effect on the radio-interference qualities of a treated unit. Experience in the laboratories has indicated the characteristics are changed slightly; these changes have generally indicated an improvement of its characteristics but not sufficient to warrant any noticeable change in line noise.

Information in regard to the expected life of asphalt emulsion is covered in my reply to Mr. Miller.

Mr. Grimes pointed out in his discussion some of the other factors that must be considered and remedied before satisfactory radio reception can be obtained by all listeners. As pointed out in the paper, the ultimate solution of this problem requires the co-operative efforts of the radio listeners as well as all the involved industries.

"Magne-Blast" Air Circuit Breaker for 5,000-Volt Service

E. W. BOEHNE
MEMBER AIEE

L. J. LINDE
ASSOCIATE AIEE

Synopsis: Fundamental principles of magnetic action and thermal reaction have been united in an original manner to create a new circuit interrupter, the "Magne-Blast" air circuit breaker. Intended for general applications in switching, controlling, and protecting 2,300- to 5,000-volt circuits, this breaker, throughout a comprehensive test program, has proved satisfactory in every requirement. An open presentation of test results shows how an efficient arc chute functions thermally to decay and extinguish the arc with a minimum of voltage disturbance. The breaker is immune to circuit recovery characteristics.

Principles of performance are discussed using the familiar terms of current, voltage, resistance, and reactance in showing their effect on the instantaneous values of phase angle, current reduction, and the attendant rates of rise of recovery voltage. The co-ordinated electrical and mechanical design is described in some detail and a typical arrangement is shown as used in a metal-clad equipment.

Background

OIL circuit breakers have a history beginning with the early application of alternating currents in the electrical power industry. Throughout this period, oil breakers have maintained a satisfactory record of performance. Failures have been rare, maintenance low, and it has been possible to build circuit breakers of all ratings. Although oil, by its presence alone, constitutes a hazard from leakage or fire, operating engineers will seldom sacrifice any of the proved advantages of modern oil circuit breakers to eliminate the rather remote hazard of fire. But, when freedom from oil is added to all the good points, an oilless breaker becomes attractive. The magnetic air breaker, though long used on d-c systems, has been of minor importance in the intermediate-voltage circuits of the utilities.

To be completely successful in competing with an oil circuit breaker, an air circuit breaker cannot afford to be its inferior in any respect. Available field experience permits a ready review of conventional air breaker performance, for manufacturers have long succeeded in maintaining the position of such breakers in the railway and industrial fields. This experience has proved these magnetic breakers handicapped in their appeal to the utilities only because of their:

1. Poor space factor.
2. Exposed flame, demanding careful segregation.
3. Visual and audible disturbance.

These same breakers, however, provide an argument to their favor in an acknowledged record for:

1. Positive circuit control.
2. Little deterioration of materials during interruption.
3. Economical operating life.
4. Simple contacts and arc-interrupting details.

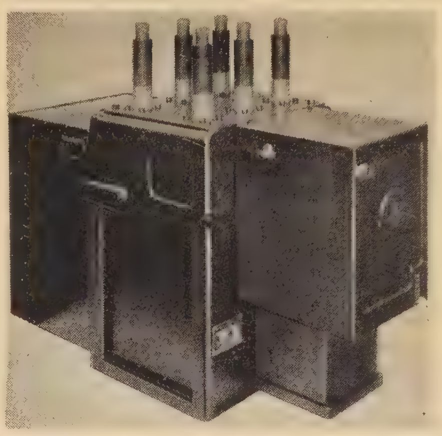


Figure 1. A left-front view of a 1,200-ampere Magne-Blast air circuit breaker for use on 2,300- to 5,000-volt circuits

Insulated for 7.5 kv, rated interrupting capacity 100,000 kva. This breaker is arranged for use in a vertical-lift metal-clad equipment

Though boasting of the obvious advantages here listed, magnetic air breakers have been forced to a secondary position by the problems of size, flame, and disturbance. The "Magne-Blast" circuit breaker offers a solution to these problems while maintaining every advantage of previous breakers.

Application

Unless custom-built to meet the requirements of a particular application, the value of a power circuit breaker is enhanced by the variety of applications it will satisfactorily meet. The breadth of this field is responsible for the variety of characteristics that are today demanded of breakers. Fortunately these characteristics may be grouped into three classes: switching, protection, and control; each making its individual demands on equipment.

Listed below are the most important characteristics of a good breaker:

1. Reliable circuit interruption.
2. High insulation level.
3. Long and economical operating life.
4. Little hazard and disturbance.
5. Small size.
6. High operating speed.

The air circuit breaker here described meets every objective listed.

Under the heading of performance will

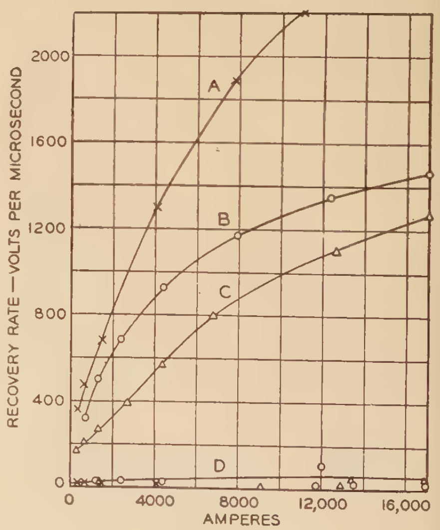


Figure 2. The influence of the Magne-Blast air circuit breaker on the voltage-recovery characteristics of typical circuits

A, B, and *C*—Characteristic rates of rise of recovery voltage for three test circuits

D—Rates of rise of recovery voltage of the same circuits during Magne-Blast circuit-breaker tests

These data were recorded with a cathode-ray oscillograph

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Reliance has been placed on the co-operative efforts of many individuals during the successful development of the Magne-Blast air circuit breaker. Appreciation is expressed for the valuable contributions from the staffs of the circuit-breaker test laboratory and the research laboratory of the General Electric Company. The Philadelphia Electric Company and the Aluminum Company of America are credited with the original applications of this breaker to their systems, thus providing initial service experience.

be found a rather thorough presentation of the interrupting ability of the breaker. The device exhibits no fire throughout the limits of its interrupting rating. This, together with desirable space factors permitted by an efficient arrangement of materials, has enabled the breaker to be applied in standard vertical-lift metal-clad gear. Here the two enhance each other, the gear providing all its many advantages of safety, installation costs, and appearance; the breaker providing safe and reliable circuit control.

The long operating life of the air device makes it particularly attractive in services where duty demands frequent operation. In fact, the air breaker makes certain industrial functional operations less complicated. For example, present - day furnace operators have learned by experience that if the breaker current is reduced before the breaker is operated, oil deterioration is reduced. This process is recommended at the sacrifice of the time to raise the furnace electrodes. The air device simplifies these industrial functions.

An exceedingly attractive feature of the new breaker is its immunity to circuit recovery characteristics. This desirable characteristic is achieved by the "Magne-Blast" arc-resistance characteristic which, in spite of the inductive properties of the circuit, holds the recovery rate and peak recovery voltage to a value which is only a weak counterpart of the circuit characteristic. These features are described in figure 2 and will be discussed later in detail. In brief, this characteristic of the breaker broadens its field of application, particularly where sudden switching surges endanger associated equipment.

Taken as a whole, this oilless device, incorporating all the sturdiness and reliability of the oil breaker, together with the attendant ease of circuit interruption, space considerations, and maintenance, offers to the industry a new interrupter which should find a wide field of practical applications.

Performance

Of all power equipment, the breaker has to meet the most unusual conditions. It must function unerringly to divorce the energy source from the circuit in distress and still function as the energy valve under all normal conditions. In addition to its protective values, the breaker may be utilized as a switching device accumulating many thousands of operations throughout the year. These, and other requirements, demand that the power breaker perform as a compact, sturdy, and co-ordinated application of mechanical and electrical principles.

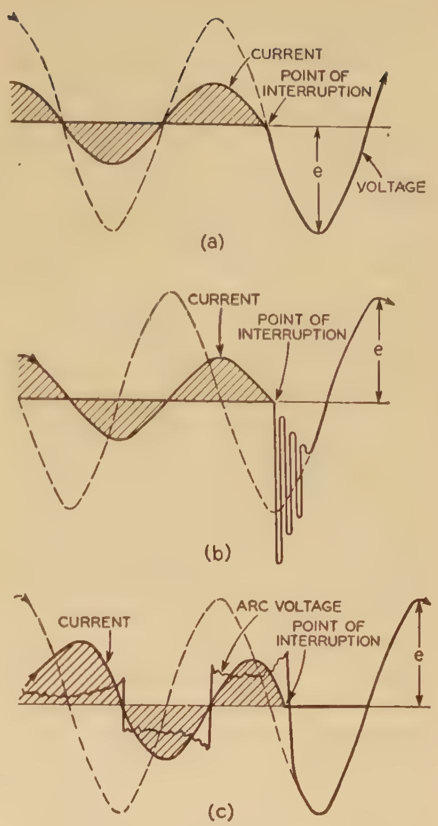


Figure 3

(*a*)—A typical interruption on a unity-power-factor circuit where the current and voltage zeros coincide

(*b*)—A typical interruption on a zero-power-factor circuit. Interruption occurs at a current zero with recovery voltage at a peak, thereby encouraging high-frequency transients and a high recovery rate

(*c*)—A Magne-Blast interruption of a zero-power-factor circuit illustrating the effect of arc resistance in shifting the current zero toward voltage zeros to reduce the rate of voltage recovery

Interrupting Performance

Table I presents a group of consecutive interrupting tests made on one three-phase breaker, rated at 5,000 volts 100,000 kva. The table presents 4,500-volt and 2,300-volt tests, showing both opening and closing-opening performance on a three-phase circuit. At the end of this series of tests the breaker had made some 870 operations, of which over 600 were made on a power life test at 750 amperes, 65 interruptions were over 50,000 kva, 40 interruptions were over

Table I. Interrupting Tests on 600-Ampere Indoor-Type Magne-Blast Air Circuit Breaker

Interrupting Rating—100,000 Kva at 5,000 Volts, Three Phase

Volts	Operation†	Test Frequency	Current (Amperes) Maximum Peak	Current (Amperes) Initial in Arc (RMS)	Three Phase Kva	Arc Duration (Cycles)	Interrupting Time* (Cycles)
2,300	O	60	690	330	1,320	5.5	9.5
2,300	O	60	1,230	660	2,600	3.0	7.5
2,300	O	60	2,600	1,150	4,600	2.0	6.8
2,300	O	60	4,000	1,870	7,500	1.7	6.3
2,300	O	60	14,500	6,200	25,000	1.0	6.5
2,300	O	60	25,000	9,600	38,000	0.8	5.0
2,300	O	60	45,000	16,800	67,000	0.7	4.8
2,300	O	60	71,000	25,000	100,000	1.0	4.3
2,300	CO	60	700	340	1,350	4.5	9.3
2,300	CO	60	1,310	710	2,800	3.3	8.0
2,300	CO	60	2,500	1,090	4,400	2 0	6.5
2,300	CO	60	4,900	2,700	10,800	1.6	6.3
2,300	CO	60	8,500	4,000	16,000	1.3	6.5
2,300	CO	60	13,300	6,700	27,000	0.9	6.0
2,300	CO	60	23,000	9,200	37,000	0.7	4.8
2,300	CO	60	45,000	19,300	77,000	0.7	5.5
2,500	CO	60	72,000	24,000	103,000	0.7	5.0
3,000	O	60	79,000	33,000	171,000	0.6	3.8
4,500	O	60	1,280	690	5,400	3.3	7.3
4,500	O	60	2,600	1,270	9,900	2.6	6.8
4,500	O	60	4,300	2,100	16,400	1.8	6.0
4,500	O	60	8,800	3,900	30,000	1.3	5.5
4,500	O	60	13,700	6,200	48,000	1.1	5.3
4,500	O	60	23,000	9,800	76,000	0.9	5.0
4,500	O	60	24,000	10,400	81,000	0.8	4.8
4,500	O	60	39,000	14,200	111,000	0.8	5.0
4,500	CO	60	1,150	510	4,000	3.5	7.3
4,500	CO	60	2,300	1,130	8,800	2.5	6.8
4,500	CO	60	72,00	3,300	26,000	1.5	5.8
4,500	CO	60	23,000	9,600	75,000	1.1	5.0
4,500	CO	60	32,000	12,200	95,000	1.1	5.0
4,500	CO**	60	30,000	11,600	90,000	0.9	5.0
4,500	CO**	60	31,000	12,900	100,000	1.0	5.0
4,500	CO**	60	41,000	15,000	117,000	0.8	4.8
4,500	CO**	60	43,000	16,000	125,000	0.6	4.5

* Times for last two phases to clear.

† O = opening, CO = closing opening.

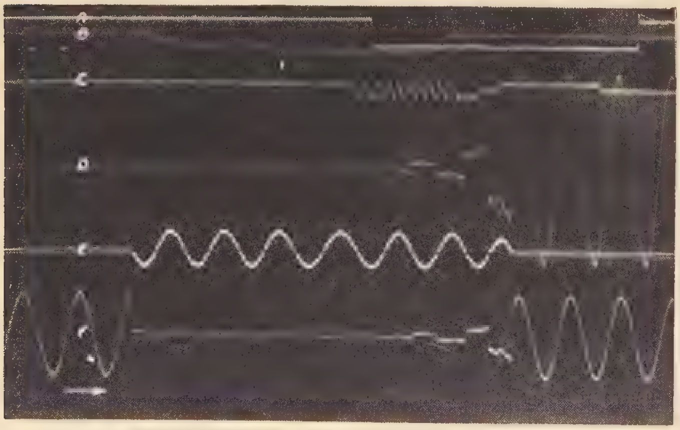
** Duty cycle CO plus 15 seconds CO.

75,000 kva, and 25 interruptions were over 100,000 kva.

The above tests were conducted on circuit connections whose recovery characteristics are described by curve *B* of figure 2. Throughout these tests frequent inspection revealed no need for mandatory maintenance. The breaker, during interruption, gave only a muffled report which was quite inoffensive. There was no visible disturbance or fire from the breaker throughout the limits of its interrupting rating. Following the above series the breaker withstood standard one-minute high-potential tests. An inspection of each chute following these tests revealed that interruption took place within the chute at a developed arc length considerably less than the longest available arc path. This knowledge was helpful in establishing a safe margin of performance to be discussed later.

A close analysis of the performance of the Magne-Blast breaker reveals a striking resemblance to the principles of interruption of a d-c circuit. That is, from the instant of contact parting the arc resistance increases. In both the a-c and d-c circuit this defines a reduction of circuit current. The a-c circuit, however, is blessed with current zeros which afford natural points of interruption. In contrast, the creation of an increasing arc resistance within an a-c air interrupting device accomplishes two major functions which co-operate to bring the current to an early interruption. These are: (1) rapid increase of energy absorption by the arc chute, interruption being forecast when the rate of absorbing the arc energy exceeds its rate of liberation, and (2) a change in the phase angle of the circuit from a zero power factor or phase angle of 90 degrees to a phase angle around 40 degrees to 50 degrees at interruption. With this changing phase angle the circuit is rapidly approaching a unity-power-factor condition where, in the limit, the current is in phase with the voltage and both approach zero together. It is common experience that the interruption of such a unity-power-factor circuit is quite easy because of the extremely low voltage following current-zero interruption. Conversely the arc of an oil breaker introduces little resistance with practically no improvement in phase angle. A breaker using oil as a dielectric withstands the full shock of the circuit recovery characteristic. Because of this fact, the true importance and significance of recovery characteristics were first revealed in connection with the oil device. This knowledge now goes forward to aid the air device. It follows, therefore, that with the decreasing phase angle and reducing arc current in the Magne-Blast breaker the recovery characteristics are improving with each successive current zero. It is of importance to note that the breaker clears when the phase angle is in the neighborhood of 40 degrees or less. The arc chute, to be described later, is uniquely designed to incorporate sufficient arc resistance to bring the circuit to within a few degrees of unity power factor had the current persisted beyond a phase angle of 40 degrees. The phase angle at interruption being approximately 40 degrees defines an ample margin in performance. These features are sketched in figure 3 showing the relationship between the recovery characteristics of a unity- and zero-power-factor interruption together with the Magne-Blast performance. The extremely high damping associated with what high-frequency transients remain in an interruption is brought about by the unique configuration which aids the gaseous products immediately following interruption to form a short-lived leakage path across the breaker. Some form of transitory leakage path has always been one of Mother Nature's methods of protecting

Figure 4. An oscillogram of a 3,600-volt 1,150-ampere single-phase interruption



A—Cathode - ray-oscillograph trip indication

B—Breaker trip-coil current

C—Breaker travel record

D—Arc voltage across breaker terminals

E—Current through breaker

F—Generator voltage

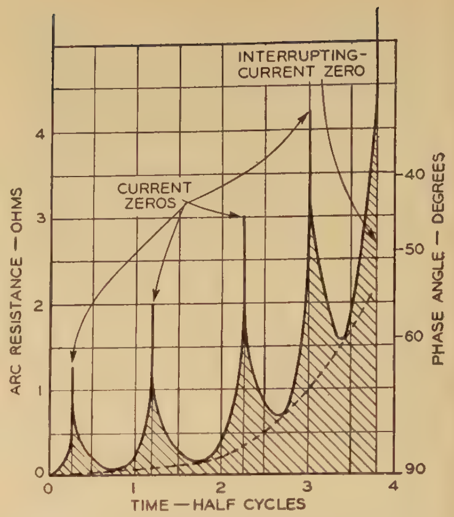


Figure 5. A curve of instantaneous arc resistance for time in half cycles

The increase of arc resistance to a circuit of constant reactance decreases the phase angle as shown. This curve is plotted from figure 3 and indicates the effect of an offset current wave

the air device. This phenomenon, working together with the large swing in phase angle exhibited by the breaker during interruption, accounts for the enormous reduction in recovery rate and peak recovery voltage immediately following interruption. This reduction in recovery rate is shown in figure 2 and forms an important link in the interruption sequence. Here, regardless of the station recovery characteristics (curves *A*, *B*, or *C*), the breaker responds with the recovery rate characteristic *D* shown at the bottom of the figure. This immunity to circuit characteristics has an important bearing on breaker application, as mentioned previously.

Figure 4 is a typical oscillogram showing a Magne-Blast breaker interruption of a single-phase fault of 1,150 amperes. The instantaneous arc resistance is defined as the ratio of the increasing arc voltage to the decreasing arc current. This instantaneous resistance is plotted in figure 5 for the test of figure 4. During any half cycle of current the minimum resistance occurs, as would be expected, near the current crest. However, this minimum resistance increases for each successive half cycle until resistance on the last half cycle of arc is such a value that the phase angle of the circuit is close to or less than 60 degrees. At the next current zero the current is invariably extinguished.

Figure 6 shows a master plot of the minimum resistance of the last half cycle of arc for the tests of table I. This characteristic is shown in both linear and

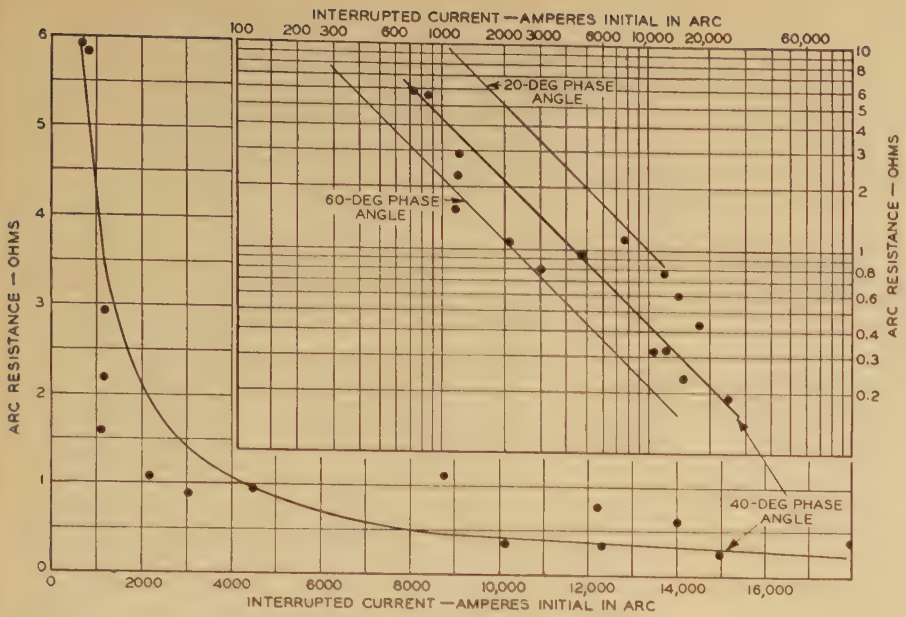


Figure 6. Shows the interrupted current, initial amperes in arc plotted against the minimum resistance introduced in the last half cycle of current

The points are plotted on logarithmic and linear scales showing the curves of the resistances necessary to give a 40-degree phase angle on both scales and the 60-degree and 20-degree phase angles on the logarithmic scale. The tests plotted on this curve are all single phase

the lower is typical of the last pole to clear. Following the first phase to clear, the remaining phases clear in series. Because of the compounding of the series arc resistances of the two remaining phases, together with the fact that they clear later, the final clearing usually takes place at an extremely low phase angle.

Before starting an extended series of interruption tests the breaker was tested to determine the effect of rapid duty. A normal operating load was established and interrupted once every 30 seconds until more than 600 operations were recorded. The breaker required no cooling as it continued its operations on this reactive circuit of 750 amperes at 4,500 volts. A series of 140 interruption tests were then completed. Of this number 65 interruptions exceeded 50,000 kva and 25 were of more than 100,000 kva. Standard one-minute high-potential tests showed no reduction in insulation values. After this complete series the breaker was disassembled and inspected. Of all details, the arcing tips alone required maintenance or replacement.

logarithmic form. The latter shows the remarkable fact of a straight line at −45 degrees slope which, in turn, defines a constant-power-factor characteristic. The phase angles of the lines shown are indicated on the curves.

The effect of arc resistance for the test of figure 4 is shown in quite different form in the static vector diagram of figure 7. Here the arc voltages for the four half cycles of the arc are shown by the horizontal vectors marked 1, 2, 3, and 4, respectively. Each half cycle of arc current is shown in instantaneous magnitude and phase-angle relationship to the circuit voltage. Figure 6 gives a graphical interpretation of the several simultaneous changes which are taking place within the circuit, namely, the current reduction, the increase in arc voltage, and the reduction of phase angle. It will be noted that the phase angle, as the current approaches its final zero, is somewhat closer to the voltage than indicated by the phase angle at the peak of the last current loop, the latter being shown in general form in figure 4. This characteristic is true of each of the current loops giving a sort of hysteresis effect. This phenomena shows that a very important cooling effect starts near the current peak continuing up to current zero. This rapid cooling as the current approaches zero plays a predominant part in determining the final clearing. It might be said that the interrupting process starts during the last quarter cycle of arc. These features will take added significance when the novel chute design, presented later, is studied from an electrical and thermal aspect.

Figure 7. Polar diagram of a low-current interruption test

The schematic oscillogram (copies from figure 4) illustrates the current and voltage traces. The polar diagram illustrates the instantaneous values of current, voltage, and phase angle for each half cycle as arc resistance increases in value

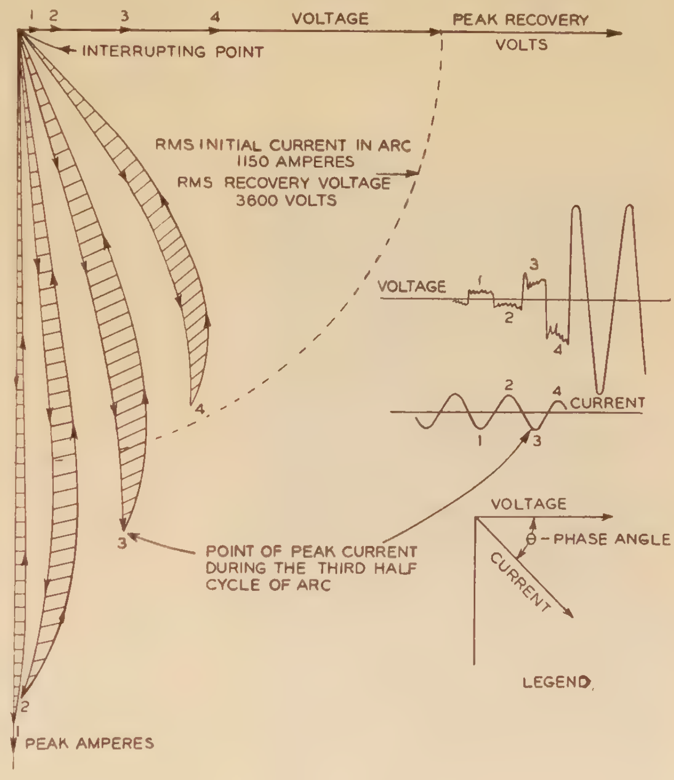


Figure 8 presents the clearing of two poles of a three-phase ungrounded fault of 125,000 kva at 4,500 volts. The upper trace shows the first pole to clear, while

Description

The performance of the Magne-Blast air circuit breaker emphasizes the importance of a controlled increase in arc resistance. This resistance can be effec-

tively increased at a controlled rate by cooling and lengthening the arc stream during circuit interruption. The interleaving or serpentine arc chute as used on this breaker, figure 9, is a simple and reliable method for cooling and lengthening the arc in a manner consistent with circuit requirements.

Interrupter

As evidenced by its name, the interleaving chute is formed by long tapered fins alternating from either arc-chute wall, extending from the throat and arc runner to the mouth of the arc chute. Placed parallel to each other and spaced to leave room for the arc to fold in and out between opposite fins, their gradual taper away from the side walls permits the arc to form in a straight line without obstruction. As the arc stream is driven deeper into the chute, however, it is gradually forced to depart from its straight line as the fins cross deeper and deeper into the space between fins of the opposing side. The arc encounters an ever-increasing cooling effect as its path becomes longer and more tortuous. Long before reaching the mouth of the chute, however, the combination of cooling and elongation has increased its resistance to a critical value and the arc is extinguished. Though a sufficient untraveled path remains to provide a greater arc resistance and a further decrease in phase angle, tests show this is but a safety factor.

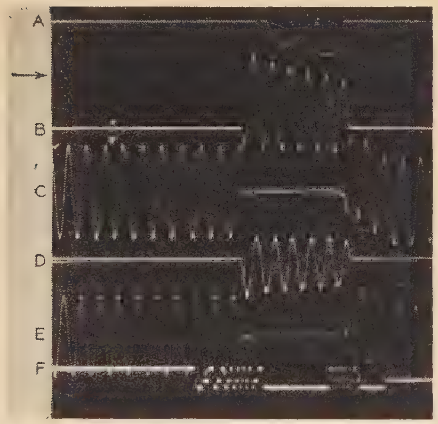


Figure 8. A representative oscillogram of two poles during a three-phase close-open test at 4,500 volts, 125,000 kva

A—Breaker-trip-coil current
B—Current, pole 2
C—Voltage, pole 2
D—Current, pole 3
E—Voltage, pole 3
F—Breaker travel

The interleaving arc chute of the Magne-Blast breaker has proved a simple way to provide ample arc cooling between closely spaced nonmetallic barriers. Arc elongation demands no compromise as the same barriers nicely fold the arc into a serpentine pattern.

The design permits moulding an arc-chute side and its fins in one piece using an especially treated arc-resistant insulation material. Continued operations show no ill effects on the chutes. Performance is unaffected, though the intense heat forms a glassy and pebbly surface on the fins. Figure 10 illustrates two sets of arc chutes. *A* shows an unused chute. At *B* is shown a chute side after 140 power tests to 130,000 kva. Color and texture have changed, but thermal and electrical properties show no adverse effects. *C*, *D*, and *E* picture the throat end, the side, and the mouth of completed arc chutes ready for mounting in a breaker.

Breaker Arrangement

Early agreement encouraged a geometric arrangement that would permit the use of the Magne-Blast air breaker in vertical-lift metal-clad switchgear assemblies. Experience with such gear using oil breakers has long proved the value of such arrangements. No compromise in performance or cost was permitted in completing the design illustrated in figure 11. Terminals, conductors, and operating structures show a close relationship to oil-circuit-breaker arrangements. A conventional oil-circuit-breaker operating mechanism is mounted on and isolated by a steel plate enclosing the front of the breaker frame. The conductors, contacts, and current coils are enclosed within the rigid breaker frame. Arc chutes, arc runners, mufflers, and box barriers extend back from the frame to define the boundaries. The arrangement is desirable from the listed advantages:

1. Compact and efficient in space.
2. Adaptable to vertical-lift metal-clad.
3. Mechanism and control accessories completely accessible.
4. Breaker completely isolated from mechanism and operating side.
5. All breaker parts are exposed by the ready removal of the insulated-box barrier.

Figure 11 illustrates the features of this arrangement in some detail. The complete interrupter and contact structure is mounted on and between the two insulated breaker bushings. These bushings are rigidly connected to the frame and to each other by a heavy insulated barrier *J*. Arc runners and blowout coils are mounted on and insulated from bushing *G*. A copper casting extending from this bushing carries the primary contact fingers *A*. These fingers complete the current circuit to the contact arm through

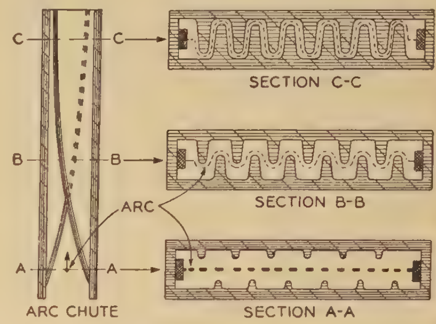


Figure 9. A schematic diagram showing the treatment of an arc in the Magne-Blast interrupter

At section *A-A* the arc is struck in a line between arc runners, as it is forced into the chute the fins constrict the arc and force it into a serpentine path *B-B*. Section *C-C* shows its final shape under extreme conditions

solid-silver inlays. The inverted arrangement of these fingers provides an increase in contacting pressure from the magnetic forces at high currents. From the movable contact arm the current enters bushing *H* at the pivot. A connection between this bushing and the lower blowout coil of the arc chute carries current during interruption and provides an additional support for the arc chute and muffler. The arc-chute assembly can be easily removed to expose the complete assembly of contacts and arc runners.

Current Transfer

To follow the treatment given the current during breaker opening, reference is made to figure 12. As the blade starts down, current is transferred from the primary contact *A* to the intermediate contacts *B*. Low-voltage arcing, as the blowout coil *E* is first shunted in, is taken on the parting of the intermediate contacts, to the benefit of the more sensitive primaries. As these intermediate contacts part, all current is shunted through the blowout coil and magnetic flux is created to force the arc on its way. Finally, the silver-tungsten arc contacts part *C*, the resultant arc is forcibly driven from the contacts adding additional blowout coils to the circuit as the arc travels along the runners *D*. For heavy currents this travel is so rapid that the arc is

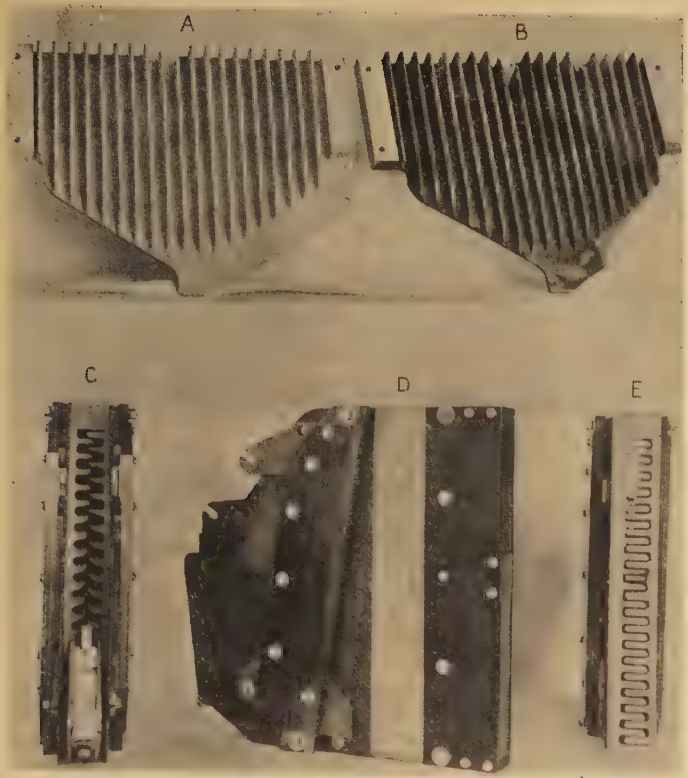


Figure 10. A finished arc chute for the Magne-Blast air circuit breaker

A—Shows one-half of an unused arc chute

B—Shows a similar half after 140 power interruptions to 130,000 kva. The discoloration of B indicates a surface change that has no effect on the thermal or electrical properties of the arc chute

C—Is taken from the throat or contact side of the arc chute

D—Shows the side of the arc chute

E—Illustrates the serpentine pattern at the mouth of the arc chute with muffler removed

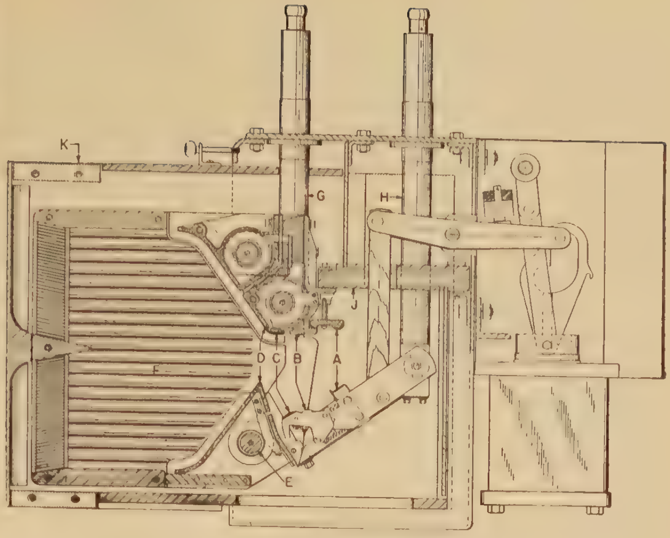


Figure 11. A sectional drawing of the 5,000-volt Magne-Blast air circuit breaker for 100,000-kva interrupting capacity

A—Primary contact fingers and movable contacts
B—Intermediate contacts
C—Arcing contacts and lower arc runner tip
D—Arc runners
E—Blowout core and coils
F—Inside of arc chute
G—Rear insulated bushing
H—Front insulated bushing
J—Horizontal tie barrier of insulation
K—Removable box barrier and vents

extinguished at a minimum break distance of one inch. As the arc terminus travels up along the upper arc runner it jumps an insulated gap and injects a second multiturn coil to maintain high flux densities in spite of current reduction. At the same time, the arc terminus has shifted to the lower runner *D* and has shunted in a third multiturn coil *E* that assists in arc travel in the lower portion of the chute. The travel of arc roots in divergent directions lengthens the arc, and, assisted by the driving force of the flux, forces it into the serpentine passage *F* on its way to extinction.

Heavy-current interruptions require throttling for the powerful magnetic blowouts at such currents may drive the arc through the chute before resistance and cooling are permitted to complete their functions. A muffler mounted on the end of the chute, pockets and retards air flow and directs all arc products into the streamlined deflectors forming the end of the box barrier. Before the gases reach this area all arc, arc flame, and gas has been cooled to a harmless value and final gases flow from the grilled openings at the top and bottom of the box barrier *K*, negligible in temperature, velocity, and potential. Maximum power interruptions are evidenced only by the small trickle of smoke from these openings and the dull thud that accompanies the formation of the initial arc.

Insulation

Bushings are designed and manufactured in accordance with oil-circuit-breaker standards. Because each pole is mounted on these bushings, the breaker is easily isolated into three phases. The extended barriers between phases and from phase to ground offer ample insulation and are flame resistant. Arc runners and blowout coils are separated from the side walls of the arc chute by sheets of inorganically bonded mica. This material, high in dielectric and mechanical strength, suffers no damage when exposed to power arcs. Operating rods of insulation are a strong link between the mechanism and the contact arms.

Operating Mechanism

Oil-circuit-breaker practices provide a valuable background when considering the requirements of an operating mechanism. Step-by-step evolution has brought the present-day solenoid mechanism to a high degree of perfection. Because this breaker so closely parallels modern oil circuit breakers in mechanical operation, it has been quite practical to use a standard operating mechanism. A modern oil-breaker solenoid mechanism contributes to performance when applied to this air circuit breaker. The mechanism requires but minor modifications when used as described. The features of an efficient

Figure 12. Contact structure and blowout coils. Half of arc chute assembly is removed

A—Primary contacts
B—Intermediate contacts
C—Arcing contacts
D—Arc runners
E—Blowout coils
F—Arc chute

solenoid structure; sturdiness, adaptability, trip-free operation, and potential- and current-transformer tripping are inherent with the mechanism used on the Magne-Blast circuit breaker (figure 1).

Arrangement in Metal-Clad Equipments

The compact arrangement of this air breaker loses no advantage when used in metal-clad switchgear equipments. Because the breaker does not exhaust hot gases beyond its barriers, the manufacturer of switchgear can use it as oil circuit breakers have long been used. Breaker compartments can be of metal with standard mechanical clearances. The breaker mechanism, control accessories, and secondary couplings are conveniently accessible from the front of the metal-clad equipment. Inspection and adjustment of these accessories can be completed without removing the breaker from its operating compartment.

Figure 13 illustrates the close relationship between such metal-clad equipments. *A* shows a metal clad using a 100,000-kva oil circuit breaker insulated for 7.5 kv. *B* shows, to a similar scale, a metal-clad equipment with a 100,000-kva "Magne-Blast" air breaker insulated for 7.5 kv.

Conclusion

The Magne-Blast air circuit breaker, by cooling and lengthening the arc in an interleaving chute, adds resistance to the circuit as the arc is extinguished. Rates of rise of recovery voltage are held to a harmless value. The breaker has demonstrated the characteristics of long and economical life, reliable circuit control, and a reduction of hot gases and disturbances when interrupting high currents. The physical arrangement permits its use in vertical-lift metal-clad gear where a compact arrangement is possible without infringing on the accessibility of the mechanism or control accessories.

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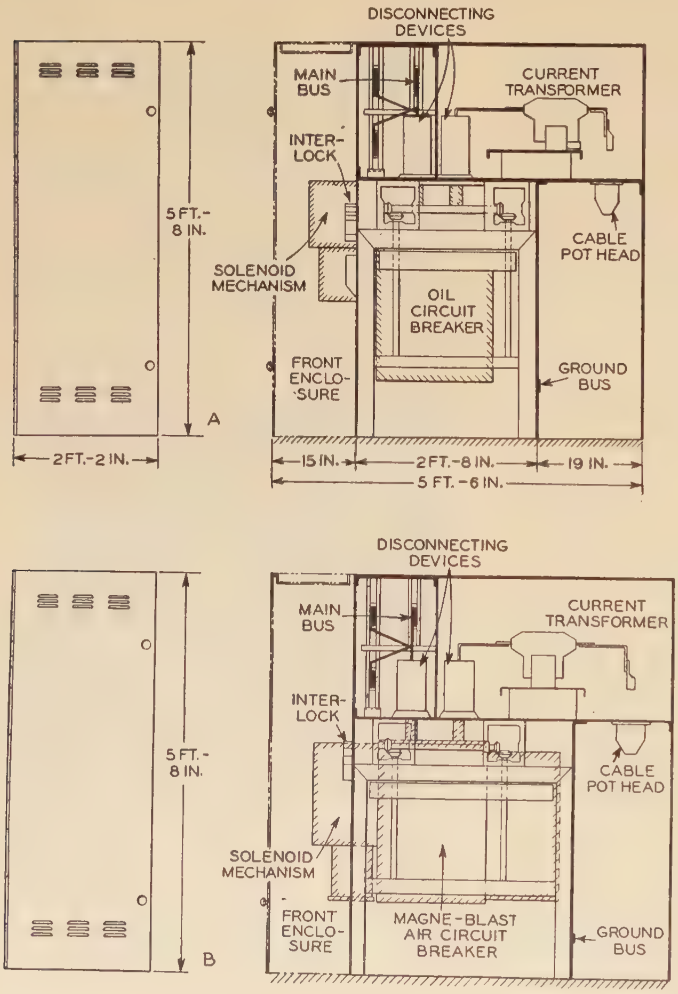

Figure 13. Breaker arrangement in a metal-clad equipment

A—An oil circuit breaker rated at 100,000 kva insulated for 7.5 kv in typical vertical-lift metal-clad equipment

B—A Magne-Blast air circuit breaker rated at 100,000 kva with 7.5 kv insulation used in a comparable metal-clad equipment

Discussion

Elias S. Cornell (Delta-Star Electric Company, Chicago, Ill.): This paper discloses an interesting development in oilless-circuit-breaker design. The mechanical and electrical complexities which seem to characterize this entire class of circuit interrupters, do not however appear to be materially reduced.

Elimination of oil or other liquids will be favorably regarded from the standpoint of maintenance. However, there appears to be a greater number of active parts such as increased number of arcing contacts, the addition of large arcing chutes, and blowout coils. Whether or not the net result will be an improved maintenance condition, only operators can tell—and time for experience should be allowed before definite conclusions can be drawn.

It is particularly interesting that this paper introduces the first oilless circuit breakers adaptable for vertical-lift type of metal-clad switchgear. Designers and operators have recognized that the vertical-lift construction possesses many electrical, mechanical, and space preserving advantages over the draw-out or truck type design.

On the other hand, modern oil circuit breakers are of clean-cut design with few working parts. Experience with this type has been so generally good that before the oilless can supplant present modern oil circuit breakers, a unit more simple mechanically and electrically must emerge from the various designs now suggested.

I shall look forward to further developments of the oilless circuit breaker of which this paper is the latest contribution.

C. G. Suits (nonmember; General Electric Company, Schenectady, N. Y.): Messrs. Boehne and Linde are to be congratulated for the excellent application which they have made of thermal principles of arc interruption. Although these principles are not entirely novel, they have been carried in the present instance to new limits which bespeak the authors' fine appreciation of the underlying arc phenomena.

The means of interrupting an arc by cooling has been employed to an accidental extent in many circuit-breaking devices in the past, but it has only been with recent advances in our knowledge of the fundamentals of this process that engineers have employed it as a design principle.

It may be of interest to review some of the fundamentals involved in the interruption principle of this circuit breaker as illustrative of the influence of thermal factors on the electrical properties of arcs.

The most important underlying fact is this: In a high-pressure discharge electrons

are in thermal equilibrium with the neutral gas, a concept first proposed by K. T. Compton.[1] The electrons acquire kinetic energy by virtue of their acceleration in the field between the electrodes, and lose a small fraction of this energy (determined by the ratio of masses) to the gas molecules in each collision. At some high gas pressure and correspondingly high collision frequency it will be impossible for the electron energies to exceed the gas energies. This implied condition for thermal equilibrium can be defined more rigorously by stating that the energy gained from the field by the electron per mean free path must be small compared to the thermal energy; thus

$$\Delta Ve << \frac{3}{2}kT$$

where ΔV is the average potential difference through which the electron of charge e falls per collision. Here k is the Boltzmann constant and T the mean gas temperature. It is clear that this relationship is best satisfied at high pressure, and since the electric field in the arc column decreases with increasing current, at high current. The results of numerous investigations[2] show that even in low-current arcs at atmospheric pressure in air the equilibrium between electrons and gas is established.

This fact has important consequences in circuit interruption, the first of which is: the *ionization density* is fixed by the *gas temperature* (identical with the electron temperature), and neither of these two quantities can be changed without altering the other. When a volume of arc gas is cooled, its ionization density is reduced thereby. Moreover, the relation between ionization density n and temperature T is a quantitative one,[3] being given by the equation

$$\log_{10}\left(\frac{n^2}{N}\right) = -\frac{5{,}040V}{T} + \frac{3}{2}\log_{10} T + 15.38$$

where V is the ionization potential of the neutral gas of molecular density N. It is interesting to note the sensitivity of ionization density to temperature, particularly at the temperatures around 2,000–3,000 degrees Kelvin which have been observed around the current zeros of some a-c arcs.[4] This is shown by table I of this discussion, where ΔT is the temperature difference required to double the ionization density at the mean gas temperature T. Thus a change of only 30 degrees will double the ionization density at 2,000 degrees Kelvin. It is not difficult to understand, therefore, how removal of heat by the circuit-breaker chute structure is effective in reducing the conductivity of the arc gas at the current zero.

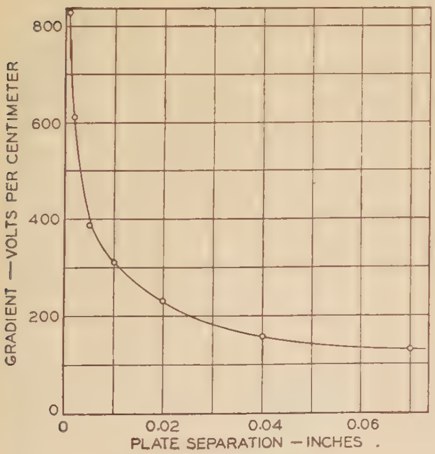

Figure 1. Electric gradient for an arc between flat insulating plates at different separations

A second consequence of the thermal equilibrium in the high-pressure arc is this: It is impossible to change the direction of momentum of the conducting electrons, as, for example, by a magnetic field, without also acting upon the neutral gas. This is a consequence of the high rate of energy transfer at high pressure. Thus we do not sweep out the electron cloud as a separable quantity with the magnetic field. We move the electrons and the gas; in short, the arc column. For that reason we find that when a d-c arc is wiggled by an a-c field perpendicular to its axis, its maximum translational velocity is a very small fraction of the velocity which it reaches in a d-c field of the same magnitude. In some unpublished calculations, Doctor H. Poritsky found that to account satisfactorily for the velocity of the arc moved by a d-c magnetic field he had to use a value of mobility corresponding not to that of the electrons, but to that of a relatively immobile body, such as a positive ion. This is further evidence that the electron gas cannot move without dragging with it the neutral gas. It has, of course, long been known that because of the space charge it is impossible to separate the electrons from the positive ions in a plasma.

Considerations such as the above lead us to the application of heat transfer data to the arc column.[5] We can move an arc magnetically past an insulating plate and in cooling it thereby reduce its ionization density. This rather striking effect can be illustrated by a simple experiment in which the electric gradient in the arc column is measured for an arc between insulating plates with various spacings, as shown by the curve of figure 1 of this discussion. These measurements were taken for a steady-state d-c arc of 15 amperes, but they are believed to be illustrative of a general property of the high-pressure arc, whether it be d-c or a-c, high or low current. Similarly, we can investigate the effect of cooling on the current zero in a transient arc. This is illustrated by figure 2, where the cooling or "deionization" time τ is plotted as a function of plate separation for an arc burned between parallel insulating plates. In this experiment the d-c arc current of 15 amperes is suddenly reduced to zero for an adjustable interval and then voltage is suddenly reapplied. The time τ is the minimum interval which will prevent reestablishment of current. It decreases with smaller plate spacing as a result of the more effective cooling.

Table I. Temperature Difference ΔT to Double Ionization Density at Mean Temperature T

T (Deg K)	ΔT
7,000	400
6,000	300
5,000	210
4,000	130
3,000	78
2,000	30

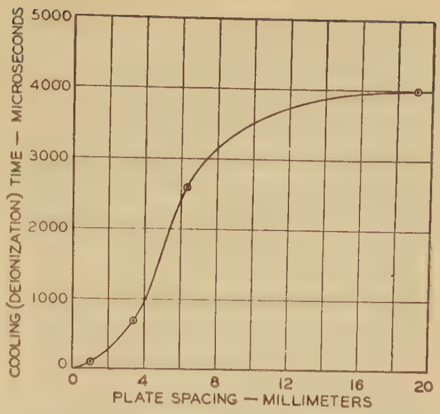

Figure 2. Cooling time of arcs between insulating plates, for different spacings

In applying heat-transfer principles to their circuit breaker, the authors have arrived at a form of cooling structure which in a unique way satisfies many diverse practical requirements in addition to the prime function of extracting heat. Thus the desirable lengthening of the arc column brings with it the advantage of a longer parallel insulation path at the time of the current zero. This particular insulation path, because of its higher temperature, is most vulnerable to surface flashover. The folding of the arc column is accomplished in the plane perpendicular to the plane of the arc motion. This is important because folding in any other plane will bring with it some components of magnetic field (due to the current upon itself) which oppose the blowout field.

It is interesting to point out that in this breaker we observe a real current-limiting action, analogous in many ways to the phenomena of the current-limiting fuse.[6] As a result of recent work we now know beyond question that this fuse is a real arc interrupting device wherein a high gradient is developed in an arc in a tube of fused quartz. This fact apparently escaped the original investigators.[7,8] These data will be reported more completely elsewhere.

That the principle of arc interruption by cooling will have wider development and that heat transfer engineering will be further applied to circuit breaker design seem certain by the remarkable performance of the authors' Magne-Blast breaker.

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R. C. Dickinson (Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): Since the announcement over ten years ago of the pioneer in the field of high-voltage high-capacity modern oilless circuit breakers, the "De-ion" air circuit breaker, several types of oilless circuit breakers have made their appearance. This latest device, presented by Messrs. Boehne and Linde, draws an arc and increases its voltage to such an extent that the circuit potential cannot maintain it. Thus, principles heretofore applied only to low-voltage interrupting devices, have been extended to a higher-voltage class. This is accomplished in approximately the space of competitive breakers by refinement in the design in the interrupting element.

It is now recognized that a good principal of circuit breaker design is to keep the arc energy of the interrupting element as low as possible, thereby minimizing distress on the breaker in general. The arc energy is a function of the integrated arc voltage with respect to time and, therefore, it has always appeared good practice either to keep the arc voltage low except near the current zero, or to keep the interrupting time very short. In view of this it comes somewhat of a surprise to hear high arc voltage in a circuit interrupting device proclaimed as an advantage.

Fundamentally, the device described seems to operate on the long established principal of stretching the arc out to great length, thereby developing sufficiently high arc voltage to prevent the circuit voltage from maintaining it. The resulting arc voltage is sufficient to cause a shifting of the point of interrupting from the crest of the a-c wave (for a zero-power-factor circuit) toward the zero point, which thereby reduces the magnitude of the resulting transient in proportion to the system-frequency phase shift. Any other reduction in the transient peak must evidently be caused by leakage. The author states that such leakage does occur in this device and that this leakage is through a path formed by gaseous products. We would expect this leakage effect to vary considerably over the interrupted current range. That is, it would be more pronounced at high current values. This would make the breaker largely dependent purely upon the development of arc voltage at the low current values. We would also expect the development of arc voltage to be decreased at low current values due to the weaker blowout effect and to the decreasing effect of the restriction of the arc path formed by the narrow serpentine slot. Therefore, we would be interested to know how this breaker performs on low current values such as magnetizing currents.

In discussing the authors' explanation of the operation of this breaker, we call attention to a statement by D. C. Prince in his discussion of "Arc Extinction Phenomena in High-Voltage Circuit Breakers Studied With the Cathode-Ray Oscillograph" by Messrs. Van Sickle and Berkey:[1] "The modification produced in the circuit recovery rate by these (oil) breakers is due to their attempting to clear the circuit at times other than normal current zero or to conduction of small currents without a complete breakdown of the dielectric. These characteristics tend to produce distress in the circuit breaker, as it is required to absorb energy normally stored in the electric circuit." We would thus conclude that this is a high-energy device and is, therefore, subject to considerable stress in interrupting short-circuit current. Thus, it is primarily dependent upon a characteristic making it necessary for it to absorb relatively high energy in order to interrupt the circuit.

In the De-ion air circuit breaker, we have a shifting of the point of interruption on the 60-cycle voltage wave which is most pronounced at high current value. As shown by the oscillogram of figure 10*A*, in the paper on De-ion air breakers for 2,500 and 5,000 volts, in AIEE Transactions for November 1938, this phase shift is of about the same order as shown by Messrs. Boehne and Linde. However, the interrupting principles of the De-ion air circuit breaker include a very definite voltage interrupting characteristic produced by the rapid growth of dielectric in a multiplicity of cathode layers.[2] Its interrupting characteristic is therefore independent of line current and, for all practical purposes is independent of the circuit recovery characteristics. The reduction in transient peak caused by the phase shift at high current in the De-ion air breaker is not relied upon for circuit interruption and is merely incidental in its performance. Also, in the De-ion air breaker, no critical damping of the recovery transient due to gaseous leakage paths has been observed.

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V. L. Cox (General Electric Company, Philadelphia, Pa.): This new design of oilless circuit interrupter will find many fields of application especially where frequent operations are necessary for motor starting, jogging, reversing, furnace control, and reclosing feeder service.

In designing this breaker, the design engineers kept in close touch with the engineers responsible for switchgear assemblies, and the result is a breaker that can be fitted into present oil-circuit-breaker equipment designs with practically no change in arrangement of apparatus and over-all dimensions. It was early recognized that the contour of the air breaker should conform as closely as possible to that of the oil breaker in order to conserve space in the usual switching structure. It has long been recognized that the most economical arrangement, for the combination of busses, breaker, current transformers, potential transformers, and the take away of primary cables (up or down) can be accomplished only with this particular contour.

The ideal structure for mounting the new breaker is metal-clad switchgear. It has been possible to retain the vertical lift, easily removable circuit-breaker feature which has been found so useful in oil-circuit-breaker metal-clad switchgear. The advantage is the continuance of a design which has proved its utility in the field; no new station designs are necessary nor need any conceptions of this type of equipment be changed.

The use of an oilless circuit interrupter in metal-clad switchgear puts the metal-clad type of switching structure even higher up the pinnacle of design attainment for factory-built shipped-assembled units. The safety to personnel, protection to circuits, co-ordinated design, ease of installation and maintenance, high level of insulation, and unit construction employed in metal-clad switchgear make this type of switching structure the best. This holds true for the oil or oilless breakers, but due to the absence of inflammable liquid, the installation of the new breakers can be made in locations not best for oil circuit breakers.

Tracing the history of metal-clad switchgear back to its inception, both in Europe and in this country, we find that there has been a definite trend from the compound and oil-filled structure insulating medium toward the air-filled type. The high-voltage air-breaker development is another step in this direction in its now complete elimination of this liquid.

D. C. Prince (General Electric Company, Philadelphia, Pa.): In domestic refrigerators we have gone through the stage of units separate, units above, and units below the box. By trying all combinations the most generally satisfactory has emerged. Likewise in the automobile, we have tried engines beneath the seats, engines in front, and engines in the rear. Each arrangement has its advantages, but, in general, the logic of the situation has begun to clarify itself.

Until recently circuit breakers were more or less alike. Then a perfect rash of variations broke out in Europe. A person fully familiar with our standard tank-type of circuit breakers might not even recognize one of the current European productions for what it is.

The use of oil in a tank determines to a certain extent the configuration of the parts of a circuit breaker. In a circuit breaker such as the Magne-Blast, this criterion is absent and in its absence the situation regarding the whole arrangement problem should be reconsidered.

In Europe the threat of war and scarcity of various raw materials may effect evolution; also, different maintenance practices and different service standards may put a premium on different elements of design. We must, therefore, go through our own evolutionary process, as we have done in connection with the refrigerators and automobiles, to see what physical arrangement, in the absence of the limitations of an oil vessel, lends itself best to the industry's needs.

This question cannot be satisfactorily answered in the laboratory. The next few years will, therefore, see many excursions away from past conventional circuit-breaker practices. In the end the most suitable designs will evolve. For the sake of the

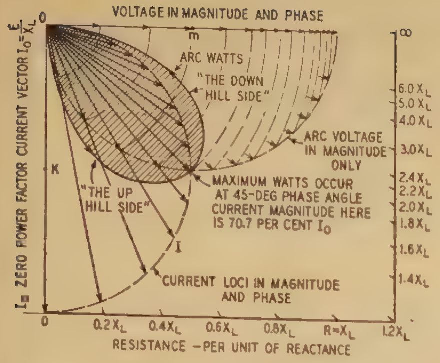

Figure 3. Polar diagram showing the inseparable relations between phase shifting, current reduction, and watts as resistance is inserted into an inductive circuit

Note: Maximum watts occur at 45-degree phase angle when the current is only 70.7 per cent of its zero-power-factor value

industry, let us hope that such evolution can be brought about with a minimum of false starts and costs for all concerned. However, nature is a severe taskmaster. We must evolve to meet changing conditions or join the dinosaur.

E. W. Boehne and L. J. Linde: The development of the Magne-Blast breaker is the natural growth of the General Electric Company's oilless devices of high interrupting capacity pioneered by our company's transportation department and presented in excellent papers in 1922 ["Air-Break Magnetic Blowouts (For Contactors and Circuit Breakers Both A-C and D-C)," J. F. Tritle, AIEE TRANSACTIONS, 1922, page 262]. The interleaving chute has enabled appropriate rating to be literally folded into sizes and arrangements suitable for standard vertical-lift metal-clad gear. The development embodies the contributions of the past, the contributions of a fuller knowledge of recovery rates as offered by the oil device; the contributions of our research studies of arcs in various environments, together with novel arrangements in mechanical design.

The authors are greatly indebted to Doctor Suits for his discussion of the problems of circuit interruption in air. His investigations of arc phenomena have considerably reduced the mysteries of such arcs and have shown us the importance of the thermal as well as the electrical factors of this general problem. The interleaving arc chute meets all thermal demands as well as the electrical requirements of an interrupting device.

Mr. Cornell points to the clean-cut design and few working parts of modern oil circuit breakers as contrasted to the apparent complexity of any oilless circuit breaker design. Blowout coils, arc chutes, and insulations do add to the complex appearance of an oilless breaker. Apparent complexity, however, can only be evaluated as it influences performance and maintenance expense. We are fortunate in having a complete historical background covering the performance and life expenses of magnetic-blowout-type air-circuit-breaker constructions. During many years the type *JR* high-voltage air circuit breaker has maintained an excellent reputation for performance and life in the industrial and transportation fields. The Magne-Blast breaker incorporates a similar blowout-coil construction.

As a contribution to easy inspection and maintenance, the enclosing box barrier may be readily removed to expose the arc chutes and contact structure. Arc chutes themselves are then easily removed when a more detailed inspection is being made, for then all arc runners, contacts, and blowout coils are accessible.

We are in agreement with Mr. Cornell and Mr. Cox in their discussion of vertical-lift arrangements. This particular breaker arrangement is a direct result of the operators' and designers' recognition of the many advantages of the vertical-lift design over draw-out or truck designs for metal-clad switchgear.

To carry through with the points raised in Mr. Dickinson's discussion requires a clarification of the principle of arc interruption as demonstrated by the Magne-Blast breaker. The basic consideration is one of resistance. When resistance is uniformly inserted into an otherwise zero-power-factor circuit, the current is reduced, the power factor swings toward unity, and energy is dissipated in the resistance. These three changes are inseparable as clearly shown in the circle diagram of figure 3 of this discussion. Energy dissipation becomes maximum when the resistance in ohms equals the reactance in ohms and occurs, as shown in figure 3, at a phase angle of 45 degrees, simultaneous with a current reduction of only 30 per cent. The Magne-Blast breaker magnetically blasts the power arc into an efficient arc trap where the resistance characteristics are uniformly developed in the arc itself, and so effectively that energy dissipation is thrown over the hump of maximum energy dissipation and, as the decaying arc proceeds in the chute, it is literally on the "downhill side" toward interruption. See figure 3.

With the above fundamental relations in mind, it is a little difficult to unravel the apparent contradictions in Mr. Dickinson's discussion to the effect that the De-ion breaker exhibits comparable phase-angle

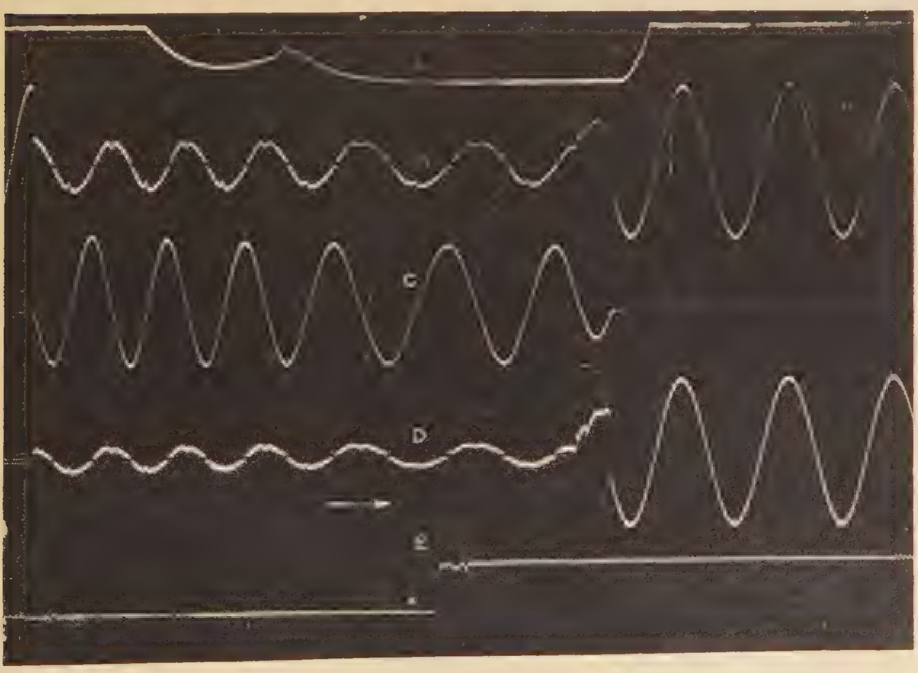

Figure 4. Single-phase interruption of 22,000 amperes at 2,600 volts by a Magne-Blast breaker

Note current reduction to 46 per cent of previous loop and low phase angle at interruption

A—Trip-coil current
B—Bus voltage
C—Short-circuit current
D—Arc voltage
E—Cathode-ray trip

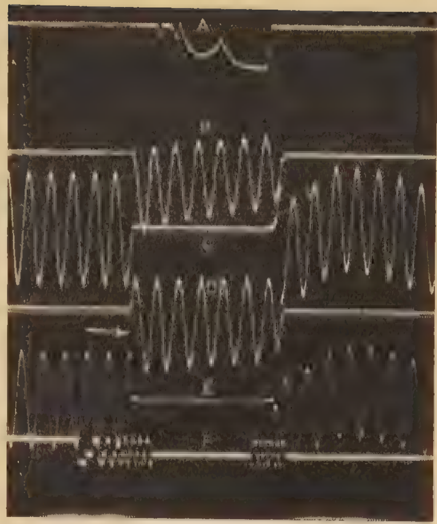

Figure 5. Oscillogram showing two phases of a three-phase CO interruption of 14,000 amperes at 4,500 volts by a Magne-Blast air circuit breaker

Note the low arc drop at current crest and the high arc drop at interruption

A—Trip-coil current
B—Phase *A* current
C—Voltage across phase *A*
D—Phase *B* current
E—Voltage across phase *B*
F—Travel record

changes, marked arc-current reduction, while paragraph 2 of his discussion teaches the merits of keeping the arc energy of the interrupting element as low as possible.

Arc energy has been no problem in the Magne-Blast breaker, chiefly due to the controlled absence of all metal vapor from the main arc stream together with the exposure of the rapidly moving arc to increasing amounts of cool insulating surfaces. In the Magne-Blast breaker the arc duration of higher currents seldom exceeds one-half cycle. In this short interval the heat penetration into the surface walls of the interleaving chute is less than eight mils. That component of heat which is retained is partly absorbed into the fins of the chute, the larger share being carried off by convection currents immediately following interruption. These conclusions are necessary to account for the fact that following an exhaustive series of tests the breaker will be found as "cool as the proverbial cucumber."

This brings us to Mr. Dickinson's recommendation of high arc voltage near current zero. We heartily agree and refer to the two oscillograms in our paper as well as the two shown in this discussion, the latter of which bears considerable study. Note the low arc voltage at peak current in relation to the high arc voltage at interruption. This is the first time that this desirable characteristic has been observed in air breakers of this type. It is the characteristic result of a pure expanding arc, confined and cooled in the absence of metal vapor.

Recovery rate control by the Magne-Blast breaker is a natural refinement of one of the inherent properties of air interrupters employing magnetic-blowout action. It has only been through the evolution of oil breakers that the importance of recovery rates has been recognized. Low-gradient leakage paths available during the first 100 microseconds following interruption afford an excellent way to absorb the high-frequency components of recovery characteristics. This leakage path is through the gas confined to the chute during a brief recovery period following interruption and has only been detected by the absence of the high-frequency component of the recovery characteristic. The extreme length of this path deep within the chute together with its freedom from metal vapor accounts for this desirable shock-absorbing feature. The major factor in recovery-rate control, as previously demonstrated, is the large phase shift up to the point of interruption.

Low-current performance of the Magne-Blast breaker follows the same characteristics as the higher-current performance, namely, a continually increasing arc voltage, phase shifting, current reduction, followed by a positive interruption. These processes are naturally slower because of the slower movement of the arc along the runners.

The Magne-Blast breaker has been tested throughout the complete current range, that is, from 0.2 amperes upward, zero-power-magnetizing currents as well as similar currents on a leading-power-factor basis. These tests have been entirely satisfactory and are strengthened by the fact that, with this publication, breakers have been in service over a year performing satisfactorily where interruptions of regulator magnetizing currents are required daily.

The Use of Multiwinding Transformers With Synchronous Condensers for System Voltage Regulation

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THREE-WINDING transformer banks offer a convenient and economical means, and are frequently used, for operating synchronous condensers at step-down substations, particularly where the secondary voltage is too high for direct operation of the condenser. The usual function of the condenser in such cases is to regulate the secondary voltage, and the condenser regulator is controlled from that voltage rather than from the tertiary winding, or condenser terminal voltage. Furthermore, in many three-winding transformer designs the effect is nearly the same as though the condenser were actually operating on the secondary winding.

There are, however, many applications in which it is desirable to vary the transformer design and with it the condenser performance in order to accomplish a particular regulating and power factor correcting job which cannot be done with the usual three-winding design. A number of such applications, involving not only three-winding transformers but in some cases four-winding transformers as well, have been worked out and placed in operation with excellent results on the system of the American Gas and Electric Company.

While descriptions and analyses of the conventional three-winding transformer design have been presented and discussed in the technical literature (see bibliography), there is believed to have been little, if any, discussion of the possibilities of manipulating the equivalent reactance network of three-winding as well as four-winding transformers in order to co-ordinate or combine the main regulating function of the condenser with other more-or-less secondary regulating effects which may be desired. It is the purpose of this paper, therefore, to describe and classify the several types of transformer designs and regulating combinations that can be used in applying synchronous condensers with multiwinding transformers and to illustrate each type with examples of actual installations.

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Theory and Application of Three-Winding Transformers

It is recognized, as mentioned above, that the equivalent reactance network of three-winding transformers derived by means of the three-point formula has been amply published before, but for convenient reference in this paper it

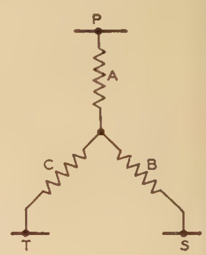


Figure 1. Equivalent-reactance network of three-winding transformer

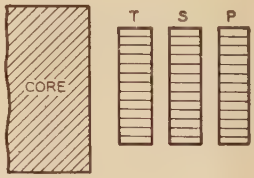


Figure 2. Probable arrangement of windings for type I transformers

will be repeated here. The reactance network as shown in figure 1 takes the form of a star in which the legs A, B, and C are found by solving the three equations:

$$A+B=X_{ps}$$

$$A+C=X_{pt}$$

$$B+C=X_{st}$$

The terms X_{ps}, X_{pt}, and X_{st} are the reactances from primary to secondary, primary to tertiary, and secondary to tertiary, respectively, expressed in per

cent or per unit values and of course all referred to the same kilovolt-ampere base. The solution of the above equations gives the following expressions for the three legs of the star:

Leg $A = \frac{1}{2}(X_{ps}+X_{pt}-X_{st})$

Leg $B = \frac{1}{2}(X_{ps}+X_{st}-X_{pt})$

Leg $C = \frac{1}{2}(X_{pt}+X_{st}-X_{ps})$

In transformers having the three windings placed successively on the core without interleaving, as shown in figure 2, one of the three legs of the star will have a relatively small value for the reason that the reactance between the two windings farthest apart will be roughly equal to the sum of the reactances between adjacent windings. For example, if in figure 2, $X_{pt}=X_{ps}+X_{st}$, then leg B in figure 1 will be zero. With interleaved windings, however, whether on the shell-type or core-type design, the straight-line reactance circuit no longer holds true and it is generally possible to obtain nearly any de-

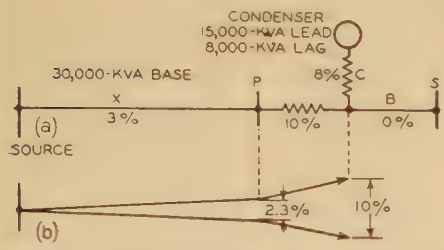


Figure 3. Typical application of type I three-winding transformer and condenser for ten-per cent no-load voltage range

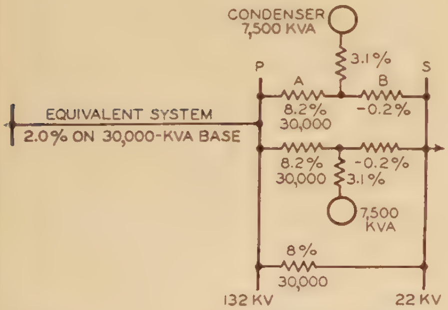


Figure 4. Type I transformer application; equivalent setup for Sunnyside substation, Canton, Ohio

sired relationship between the values of A, B, and C in figure 1.

When a synchronous condenser is connected to leg C of figure 1, obviously the relative values of A and B will directly affect the regulating performance and the range of voltage control obtainable with a given size of machine. The particular problem which will be dealt with in the discussion of the various types of installations presented in this paper will be the selection of these relative values, A and B, in the equivalent reactance network. The value of C affects the range of terminal voltage over which the condenser is required to operate, but for this discussion it will be assumed, as is generally true, that it offers no serious problem except the necessity of selecting the proper voltage ratings for condenser and transformer.

For convenience, the three-winding transformer designs discussed in this paper will be classified in three types according to the relative location of the synchronous condenser in the equivalent reactance network, that is, according to relative values of A and B in figure 1. The reason for this classification will appear in the following descriptions.

Type I—Conventional Three-Winding Designs With Condenser Regulating Secondary Voltage

In this type the equivalent reactance network of the transformer places the condenser electrically on or close to the secondary bus. A typical elementary layout for such a transformer and condenser combination is shown in figure 3a where the equivalent circuit legs A, B, and C correspond to the equivalent circuit shown in figure 1 and the transformer design would probably correspond to figure 2. To illustrate the actual performance of such a setup, typical values have been assigned as follows:

Transformer bank = 30,000 kva

Condenser rating = { 15,000 kva lead; 8,000 kva lag }

Equivalent reactance network of transformers:

$A = 10$ per cent
$B = 0$ per cent
$C = 8$ per cent

Equivalent system reactance to high side of transformer = 3 per cent on 30,000 kva

The proper system reactance to use in this elementary diagram is not the total reactance back to the source, including generator reactances, etc., but only that part of the system reactance between the point of installation being considered and the nearest point or combination of points at which system voltage is normally maintained at a constant level. This value of reactance will usually be much smaller than the total system reactance ordinarily used to determine short-circuit current at the particular location. This reduced value of reactance is used in all the elementary diagrams covering the actual installations described below.

Fig. 3b shows graphically the voltage range over which the condenser by itself with no load on the system would be able to swing the secondary voltage,

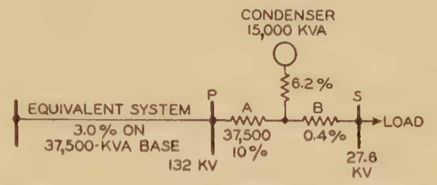


Figure 5. Type I transformer application; equivalent setup for Riverside substation, Benton Harbor, Mich.

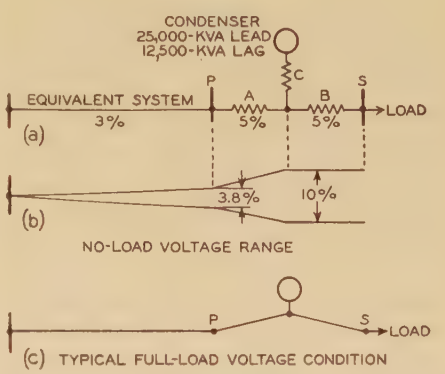


Figure 6. Typical application of type II three-winding transformer and condenser for ten-per cent no-load voltage range

in this case a total of ten per cent. This means, in other words, that the condenser would be capable of maintaining flat regulation on the secondary bus if the natural regulation due to load variation amounted to ten per cent without correction.

Typical three-winding transformer installations of the type I design on the American Gas and Electric Company system are in service at Sunnyside substation, Canton, Ohio, and Riverside substation, Benton Harbor, Mich. Equivalent reactance diagrams for each of these installations are shown in figures 4 and 5, respectively. In these installations as in a number of others of the same type, the condenser or condensers are arranged to regulate the secondary bus voltage and, as far as electrical performance is concerned, the condensers might just as well have been connected directly to the secondary bus. The only purpose of the three-winding transformer is to avoid the necessity of a second transformer bank and associated switching equipment which would otherwise be required to operate the synchronous condensers.

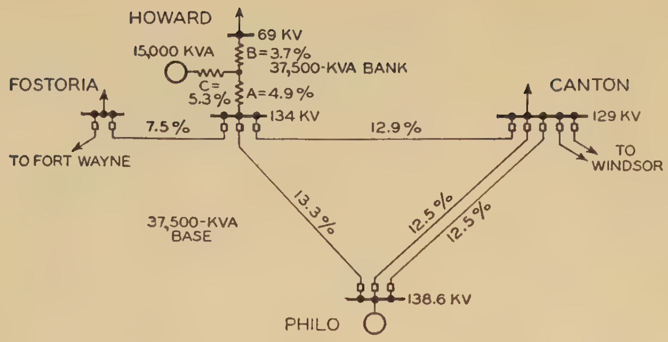


Figure 7. Type II transformer application; equivalent setup for Howard substation, near Shelby, Ohio

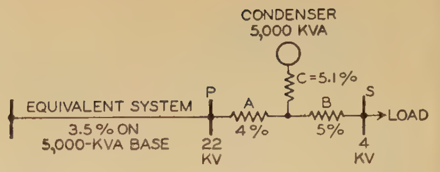


Figure 8. Type II transformer application; equivalent setup for Carbondale substation, Carbondale, Pa.

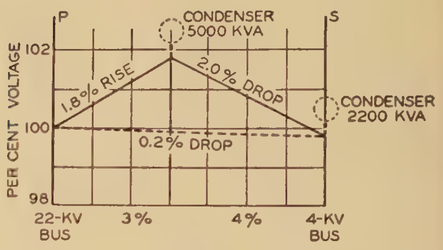


Figure 9. Comparison of condenser capacity required with three-winding and two-winding transformers, for Carbondale substation, Carbondale, Pa.

Type II—Special Three-Winding Transformer Designs With Condenser Regulating Secondary Voltage But With Increased Effect on Primary Voltage

In this type of three-winding transformer design the equivalent reactance circuit is such that the condenser is connected electrically somewhere in between the primary and secondary windings as shown in the typical elementary diagram of figure 6*a*. In this diagram, in which the system reactance and transformer bank rating are the same as in figure 3*a*, it is seen that in order to obtain the same no-load regulating range for the secondary voltage, as indicated graphically in figure 6*b*, it is necessary to use a synchronous condenser of nearly double the size. Figure 6*c* shows graphically a typical full-load condition for this setup, in which it will be observed that the condenser must be larger, not only because the total reactance *A* plus the system reactance, on which the condenser operates is smaller than in figure 3*a*, but also because of the necessity of overcoming the uncorrected voltage drop in leg *B* produced by the secondary load.

The purpose of such a transformer design is to provide regulation, primarily for the secondary bus voltage, but at the same time to utilize *more* synchronous condenser capacity than would be required with the type I transformer design, thereby giving greater correction to the high-voltage system. If the daily load curve for the local load supplied from the secondary bus is somewhat similar to the high-voltage-system load curve, then t is possible with this scheme to obtain fairly flat regulation on the high-voltage bus at the same time that the secondary bus is being held constant. To approach this result it is a fairly simple matter to determine the relative values for *A* and *B* and the condenser capacity required, taking into account of course the system load and impedance characteristics and the local secondary load.

Obviously, the larger leg *B* (figure 6*a*) is made with respect to *A*, the greater the condenser capacity required to hold the secondary voltage constant. Often the condenser size is limited by the size of the transformer bank, which in turn is fixed by the amount of secondary load to be handled. In such cases the problem becomes one of selecting relative values for legs *A* and *B* which will require a given condenser to work through a reasonably full range while regulating the secondary bus voltage. In this way the high-voltage system is given the benefit of as much correction as the capacity of the particular condenser will permit, but without sacrificing the main function of secondary bus regulation.

One of the first examples of this type of application was that installed at the Howard substation as shown in figure 7. Here the condenser rating of 15,000 kva was chosen by bank capacity and for other reasons, and it was desired to give the 132-kv system the full benefit of the condenser output while regulating the 66-kv bus. This was particularly important in this case in order to help supply the flow of reactive kilovolt-amperes required between Howard and Canton, the latter being a low-voltage point on the system because of previously installed transformers rated at 120 kv. Here, the division between *A* and *B* is in the proportion of 57 per cent to 43 per cent of the total reactance from primary to secondary which falls within the manufacturer's tolerance on a specification calling for a 60 per cent and 40 per cent division.

The operating results with this setup have been satisfactory and the condenser is still holding good voltage on the 66-kv system, although with the present heavier 132-kv system power flow, which was not altogether foreseen at the time of the installation, it would have been better to have placed the condenser a little closer to the 66-kv bus. On the other hand, this defect has been fully compensated by a subsequent installation of a much larger synchronous condenser on the 132-kv system at an adjacent station (Fostoria), which will be described later under four-winding transformers.

The use of this type of three-winding transformer is not confined to instances where the secondary voltage is too high for synchronous-condenser operation. Figure 8 shows the Carbondale substation and the equivalent connected 22-kv system of The Scranton Electric Company, where it was desired to regulate the 4-kv bus and at the same time to provide as much correction as possible for the 22-kv system. Here a 5,000-kva synchronous condenser, which is much larger than would have been necessary for regulating directly on the 4-kv bus, is used effectively by connecting it to the 4-kv tertiary winding of a 3-winding transformer bank. Figure 9 shows an analysis, confined to the transformer circuit alone, which was made prior to this installation to show a comparison between the condenser capacity required to overcome the transformer drop under a given load, first, with the condenser directly on the 4-kv bus and, second, with the condenser on the tertiary winding of a three-winding bank of the design shown in figure 10. Of course, the comparison shown here was not quite complete because of the omission of the system impedance back of the 22-kv bus. Actually, the difference between the condensers required in the two setups would be somewhat less due to the effect of this difference in condenser capacity on the system impedance, as brought out in the discussion of figure 1.

This installation has been in operation for some time and approaches flat regulation for both 4-kv and 22-kv bus voltages.

It is possible in certain cases to obtain the advantages of the type II three-winding transformer design by adding an external reactor to an existing two- or three-winding transformer bank. In the Suburban plant setup, shown in elementary form in figure 11, it was desired to install a synchronous condenser to regulate the 4-kv distribution bus, but at the same time to furnish the maximum amount of much needed reactive kilovolt-ampere correction to the 22-kv and 66-kv systems. This result was made possible by installing the 10.8 per cent reactor, shown as leg B in figure 11, and connecting the synchronous condenser to an auxiliary 4-kv bus connected directly to the terminals of the transformer bank. This scheme not only made it possible to deliver practically double the amount of reactive correction to the 66-kv system but also reduced the short-circuit problem on the 4-kv distribution bus. To make the scheme adjustable, both for present as well as future requirements, taps were provided in the reactor.

Other notable installations of type II three-winding transformers with synchronous condensers are now under construction and will be placed in operation during the present year at Torrey substation at Canton, Ohio, and at New Carlisle substation near South Bend, Indiana. The former is a 30,000-kva transformer-bank installation, and the latter, 45,000 kva.

Type III—Three-Winding Transformer Design With Condenser Regulating Primary Voltage

In this type of three-winding transformer design, the equivalent reactance network is such that the condenser is connected electrically close to the high-voltage winding and therefore is capable of effectively regulating the high-voltage bus only. In other words, leg A in the equivalent network is small with respect to B. A typical elementary diagram is shown in figure 12 where the values used correspond to those of figures 3 and 6. Obviously, such a setup does not provide a practical means of regulating the secondary bus voltage since large swings in primary voltage and a very large condenser would be required in order to compensate the drop through leg B of the transformer. It might be used, however, where it is desired to maintain constant voltage on the high-voltage bus, and by providing separate means, such as automatic tap changing under load, for regulating the secondary bus.

No setups of this type involving three-winding transformers and synchronous condensers are in operation on the American Gas and Electric Company system, although the four-winding transformer installations described below are similar in performance and purpose to this type.

Special Four-Winding Transformers With Synchronous Condensers or Generators for Regulating More Than One Bus Voltage

In 1935 a proposed synchronous-condenser application together with a new transformer bank to be installed at the Fostoria substation presented a somewhat unusual regulating problem. An existing installation of a 20,000-kva three-winding transformer bank, stepping down from 132 kv to 66 kv with a tertiary winding operating two 5,000-kva synchronous condensers, was totally ineffective for regulating the 66-kv bus because the transformer design was type III instead of type I. The existing transformer bank was fortunately quite suitable for use at another location where additional capacity without synchronous condensers was needed. In replacing this bank it was desired to provide for the operation of a large synchronous condenser to maintain bus voltage on the 132-kv system, and at the same time it was necessary to provide some means of regulation for the 66-kv bus.

The first plan proposed for this job was to use a type III three-winding transformer bank with load-ratio-control in the 66-kv winding, and to transfer the two 5,000-kva condensers to some other location. The plan finally worked out, however, made use of a four-winding transformer, designed along the lines shown in figures 13 and 14. The two 5,000-kva synchronous condensers were connected to a fourth winding so placed with respect to the other windings that effective regulation of the 66-kv bus could be obtained at the same time that the large condenser was regulating the 132-kv bus. As shown in figure 14, which represents an approximation of the equivalent reactance network of the four-winding transformer bank, the electrical effect is simply as though the large condenser were connected directly on the 132-kv bus and the two small condensers directly on the 66-kv bus. While the rigorous representation of the reactance network of a four-winding transformer bank involves a complicated solution such as that worked out by F. M. Starr,[6] the actual diagram did not differ greatly from the simple straight-line equivalent circuit shown in figure 14 and produced by an arrangement of windings on the transformer core as shown in figure 13. The transformers were specified, designed, and purchased to meet approximately the equivalent-reactance circuit of figure 14.

For regulating the 132-kv bus, there was purchased a synchronous condenser having a continuous rating of 36,000 kva at 15 pounds hydrogen pressure, and provided with sufficient excitation voltage and capacity to give a short-time ceiling overload rating of 75,000 kva.

Since the two 5,000-kva condensers were built for 4,000-volt operation, whereas a rating of 11,000 volts was chosen for the new condenser, a con-

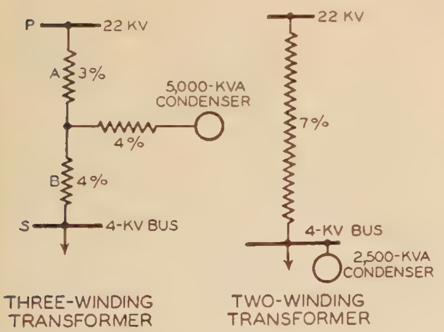


Figure 10. Equivalent networks of three-winding and two-winding transformers used for comparison in figure 9

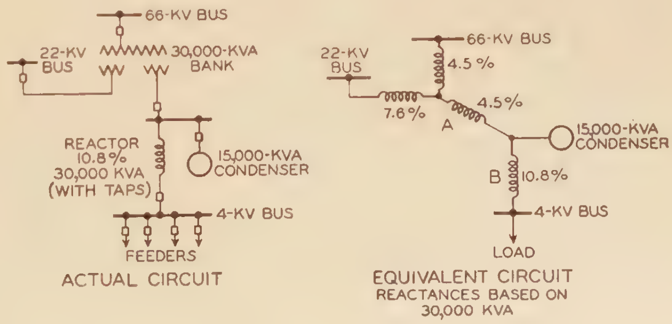


Figure 11. Simulation of type II transformers by adding reactor between load and condenser—Suburban plant, Scranton, Pa.

venient incidental feature of the four-winding transformer design was the use of the 4,000-volt condenser winding for starting the large machine, thus eliminating the necessity for compensator

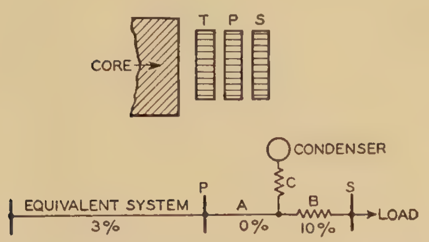


Figure 12. Probable arrangement of windings and typical application of type III three-winding transformer with condenser regulating high-voltage system only

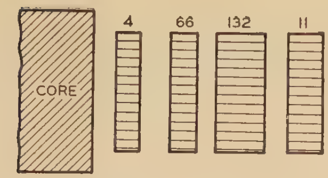


Figure 13. Winding arrangement for four-winding transformers, Fostoria, Ohio

or starting taps. Besides furnishing about the right voltage for starting purposes, this arrangement, with the two 5,000-kva condensers running while starting the large machine, offered the additional advantage of supplying a large part of the starting kilovolt-amperes directly, thereby reducing the disturbance on the system.

The performance of this installation has been eminently satisfactory, both from the standpoint of the 132-kv system regulation and the 66-kv bus regulation. One 5,000-kva condenser has been sufficient much of the time for maintaining 66-kv bus voltage. Some time after this installation was completed there was staged a test to determine the ability of the 132-kv system, together with this condenser installation, to handle heavy emergency power flow into Indiana. During these tests approximately 150,000 kw was delivered over the 132-kv system into Fort Wayne while the three Fostoria condensers delivered a combined output of more than 60,000 reactive kva. The voltage on the 132-kv bus is purposely allowed to droop at a greater rate when the condenser load goes above 36,000 kva than at loads below this value. The reason for this is to hold in reserve as much condenser capacity as possible and for as long a time as possible before the output of the machine is automatically cut back because of excessive field temperature. The inherent droop in the electronic regulator is approximately one per cent from zero to 30,000 kva on the condenser, with an additional droop of between three per cent and four per cent in going from 30,000 to 75,000 kva.

A more recent and somewhat larger four-winding transformer bank, having some of the same characteristics as that at Fostoria, was designed and installed for use with the high-pressure superposition turbine at Logan, W. Va. The elementary diagram showing the approximate reactance relationships between the four windings of this bank and the adjacent system connections is shown in figure 16. The relative arrangement of windings is shown in

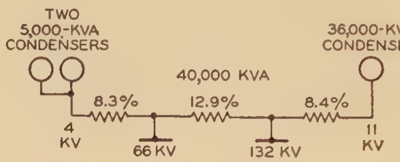


Figure 14. Approximate equivalent reactance network for Fostoria four-winding transformers

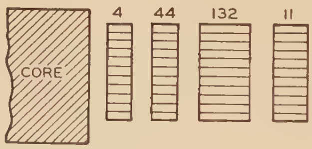


Figure 15. Winding arrangement for four-winding transformer, Logan, W. Va.

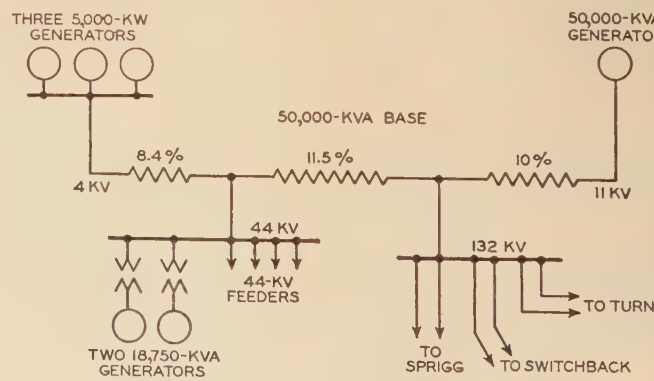
figure 15. It will be noted that the 50,000-kva generator is connected in effect close to the 132-kv bus and is arranged to maintain voltage on that bus. The two 18,750-kva generators are connected directly through step-up transformers to the 44-kv bus, and the three small machines on the 4-kv winding are coupled fairly close to the 44-kv winding but remote from the 132-kv and 11-kv windings. In this setup the 44-kv bus voltage is controlled by means of the two 18,750-kva generators, while the three small machines are expected to operate without regulation and with a fixed field setting near unity power factor to obtain maximum kilowatt output from the generators. The 50,000-kva machine regulates voltage on the 132-kv bus through the use of a resistance-reactance compensator in conjunction with the generator terminal voltage and the load delivered to the transformer.

This installation has worked out entirely satisfactorily in performing the regulating functions for which it was designed. As in the case of the Fostoria transformer bank, the rigorous equivalent reactance network of the transformer bank would be somewhat more complicated but the coil arrangement and approximate reactances specified and obtained for the bank gave very nearly the straight-line reactance diagram shown in figure 16. A photograph of one unit of this transformer bank is shown in figure 17.

Conclusions

It will be seen from the above descriptions of actual installations on the American Gas and Electric Company system that three-winding and four-winding transformers properly designed have become a rather important tool for use in our system planning. In any large interconnected network such as this, having many important load and generating points, with a wide variation both in direction and amount of power flow, it is becoming increasingly necessary to operate to a large extent at fixed voltage levels throughout the system. Of course, a certain amount

Figure 16. Approximate equivalent reactance network for four-winding transformers and station layout at Logan, W. Va.



of voltage gradient is always necessary to keep within economic limits of synchronous-condenser capacity but these voltage gradients are not allowed to become extreme. Important generating stations maintain a voltage of approximately five per cent above the nominal 132-kv level, while the low points on the system, with one or two exceptions, do not fall below 132 kv. Under these conditions, heavy power flow in any given direction for any considerable distance necessarily involves leading power factor, that is, a reverse flow of reactive kilovolt-amperes, most of which must be supplied by synchronous condensers. The special designs of three-winding and four-winding transformers described herein have contributed very substantially to the solution of the problem of maintaining reasonably constant voltage levels under these conditions of operation on the 132-kv system. In addition a number of regulating problems on lower-voltage systems have been efficiently handled by their use.

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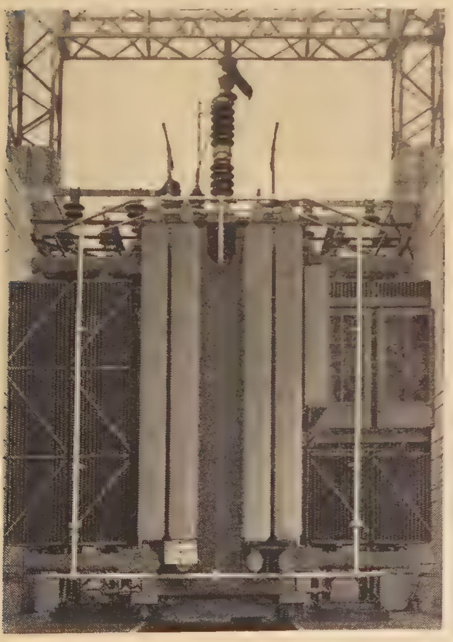

Figure 17. One unit of 100,000-kva four-winding transformer bank at Logan, W. Va.

Discussion

Wm. R. Brownlee (The Commonwealth and Southern Corporation, Jackson, Mich.): The concept of an equivalent system reactance against which a change in reactive kilovolt-amperes on a synchronous machine operates is almost indispensable for intelligent planning or even for best operation of interconnected synchronous equipment. Many have unquestionably used it in some form without a thorough understanding of the principles which have been so clearly illustrated by the author. He is to be congratulated on the clearness with which he has reduced the handling of reactive kilovolt-amperes to simple terms, and for securing valuable system characteristics at little or no increase in capital expenditure through proper advance planning.

Naturally the concept of a change in reactive kilovolt-amperes at one point of a system operating upon its equivalent reactance is based on the assumption that the resulting redistribution of reactive kilovolt-amperes between various machines will not cause any of them to reach their operating limits. This will usually be true in practical problems, but the incremental reactive-kilovolt-ampere values which are readily given by a calculating board or analytical study (necessary to determine the equivalent system reactance) will provide a simple check. In case the ability of any machine is exceeded, its connection on the calculating board may be removed from the supply bus (or common bus when considering tap changes). Results will include the variation in voltage on the "regulated" bus where the limits of machine abilities are reached.

A useful corollary of this principle is that a change in reactive kilovolt-amperes or a transformer tap change on an interconnected system will not cause any incremental flow of reactive kilovolt-amperes over any line or impedance branch which directly joins two regulated busses (assuming the machine abilities are not exceeded). Accordingly, such branches may be omitted in arriving at equivalent system reactance.

L. H. Hill (Allis-Chalmers Manufacturing Company, Milwaukee, Wis.): One of the noticeable trends in transformer design and application during the past few years has been the increased number of multiwinding transformers. Not so many years ago a three-winding transformer was considered comparatively unusual, but today three-winding transformers are comparatively common. The number of four-winding transformers that have been actually used so far has been relatively small, but Mr. St. Clair has ably indicated some of the applications for this type of transformer.

It might be interesting to point out from the manufacturing point of view that the construction of a four-winding transformer introduces no great technical difficulties. As far as the electrical design of the transformer is concerned, the principal problem consists in arranging the windings to obtain the desired reactances. In the case of core-type transformers generally used in the smaller sizes, the number of possibilities is limited due to the fact that it is usually desirable to use concentric windings. In the larger sizes, however, where the shell type of construction is frequently used, the windings can be grouped so that almost any combination of reactances may be obtained without sacrificing other desirable characteristics in the transformer. Having made an electrical design to suit the reactances desired, the only remaining added complications to the ordinary transformer are the greater number of bushings required and the greater number of terminal boards needed. In smaller sizes of transformers it may be difficult to obtain the necessary clearances for terminal boards and bushings without resorting to a tank larger than necessary, but in the larger sizes the necessary space is usually available.

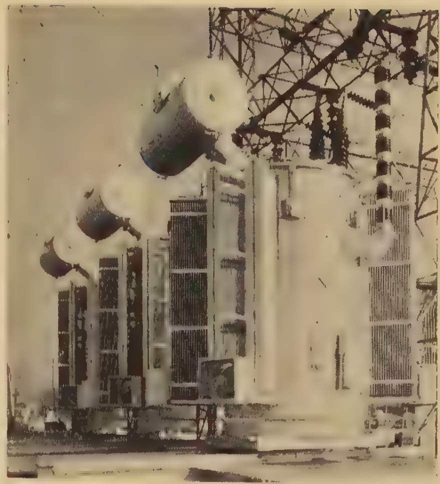

Figure 1

Mr. St. Clair describes an installation of four-winding transformers at the Fostoria substation, and figure 1 of this discussion illustrates three of the transformers before the spare unit had been installed. The complete rating is as follows:

High voltage 13,333 kva, 138 kv	single phase, 60 cycles
Second voltage 6,667 kva, 69 kv	
Third voltage 12,500 kva, 11 kv	
Fourth voltage 4,000 kva, 4 kv	

H. P. St. Clair: Mr. Hill mentioned some of the principal problems which have to be met and solved in the design, construction, and assembly of multiwinding transformers.

In regard to the problem of arranging the windings to obtain the reactances desired, we have made it a point to co-operate closely with the designers by making available to them as much flexibility as possible without sacrificing the main regulating function which is desired in a particular application. In this way, we have tried to avoid penalizing the transformer design from the standpoint of cost because of the reactances requested. In a very few cases a certain amount of penalty in cost may have been unavoidable, but, if so, the improved over-all operating results obtained were worth the small additional cost. In general, however, it is possible to work out a satisfactory design to accomplish the desired results without any increase in cost.

Wave Shape of 30- and 60-Phase Rectifier Groups

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MEMBER AIEE

As pointed out in a number of recent papers,[1,2] a mercury-arc rectifier draws a distorted current from the a-c supply system, even though power to the system is supplied by a sine-wave source. The harmonics in the current wave react on the supply system to cause distortion in the voltage wave, the degree of distortion being a function of the rating of the rectifier, the number of phases in which power is supplied to the anodes, the impedance at harmonic frequencies of the supply system, and the rectifier load. It is well known that, in theory at least, reductions in the wave-shape distortion may be effected by increasing the number of rectifier phases and thus reducing the number of harmonic components present in the supply-circuit current.[1,2] Up to 1937, however, because of practical difficulties, largely in the design of the complex transformer arrangement required, no attempts were made to produce rectifiers commercially having more than 12 phases.

Recently the Aluminum Company of America installed rectifiers having a total capacity of 82,500 kilowatts for conversion of alternating to direct current in its plants at Alcoa, Tenn., and Massena, N. Y.[3] These are the largest installations of rectifiers supplied from overhead transmission systems in this country at the present time. The power supply at both Alcoa and Massena may be interconnected with several high-voltage networks, which in turn supply several power distribution systems involved in exposures with open-wire telephone lines. Co-operative studies were made to determine the effects of these rectifiers on the wave shape of the a-c supply systems and the telephone-circuit noise. These studies were carried on during 1937 and 1938, and included preliminary estimates of the harmonic components arising in the rectifiers and their effect on the power-system wave shape. The estimates indicated that the operation of the rectifiers could be expected to increase the inductive influence of the power-supply networks over the area affected, with resultant increases in the telephone circuit noise. Tests made after half of the rectifiers were in operation at Alcoa confirmed the results of the estimates and indicated the necessity for a reduction in the rectifier harmonics.

Because of the size of these installations, and the complexity of the supply systems, it appeared impracticable to limit the rectifier harmonics by the use of frequency-selective devices, which have been successfully applied to certain smaller installations.[1] However, theoretical considerations and tests on a miniature rectifier set simulating the electrical characteristics of the converters under consideration, indicated that substantial reductions in the wave-shape distortion might be effected through the use of a relatively simple installation of phase-shifting transformers. Following the successful application of this idea in the case of the miniature rectifiers, a set of full-sized phase-shifting transformers was built and applied to each group of five 5,500-kw rectifiers at Alcoa. This arrangement reduced the important harmonic components on the power-supply systems to relatively small values, and restored the wave shape and noise conditions practically to normal. This paper describes briefly the voltage and current relations, the preliminary tests on the small-scale rectifier equipment, the phase-shifting transformers and their application to this particular situation, and presents data to indicate their effectiveness.

Harmonics in Power Supply to Multiphase Rectifiers

A number of different transformer connections[4] are used to secure six-phase operation of a rectifier when supplied from a three-phase source. For all of these connections there is a 60-degree phase relation between the fundamental-frequency voltages applied to anodes which fire consecutively, and the lowest-order harmonic component appearing in the d-c voltage wave is the sixth (360 cycles for a 60-cycle supply system). The corresponding components in the a-c supply are the fifth and seventh harmonics (300 and 420 cycles). All harmonics of order ($6a \pm 1$), where a is any positive integer, appear in the a-c supply.

In order to increase the number of phases beyond six, it is necessary to ar-

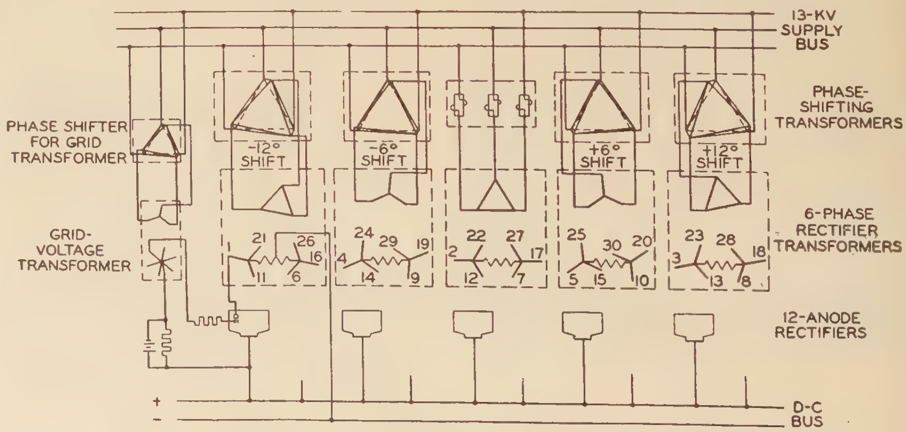
Figure 1. Schematic diagram of transformer connections in 30-phase rectifier station

Notes:

1. Connections shown for only one six-phase secondary on each rectifier transformer. Actually in each transformer there are four groups of secondaries operated in parallel supplying a total of 24 anodes in two rectifier tanks

2. Numbers on transformer secondaries indicate firing order of anodes in the five-unit station (30-phase operation)

3. Dotted Δ of phase-shifting transformers indicates supply-bus voltage; heavy lines refer to voltages applied to rectifier transformer primaries



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O. K. Marti is engineer in charge of rectifier design, Allis-Chalmers Manufacturing Company, Milwaukee, Wis.; T. A. Taylor is a member of the technical staff, Bell Telephone Laboratories, Inc., New York, N. Y.

Acknowledgment is made to the Aluminum Company of America and to the various power and telephone companies co-operating in the field tests at Alcoa, Tenn., and Massena, N. Y.

1. For all numbered references, see list at end of paper.

Table I. Theoretical Relationships in Multiphase Rectifiers

Equivalent Number of Rectifier Phases	Phase Relation Between Fundamental-Frequency Voltages Applied to Anodes Which Fire Consecutively (Deg)	Lowest Order Harmonic in D-C Output	Lowest Order Harmonic in A-C Supply
6	60	6	5, 7
12	30	12	11, 13
18	20	18	17, 19
24	15	24	23, 25
30	12	30	29, 31
36	10	36	35, 37
48	7.5	48	47, 49
60	6	60	59, 61

range the rectifier transformer connections so that the phase angle between the fundamental-frequency voltages applied to two anodes which fire consecutively is less than 60 degrees. One method of accomplishing this is by multiple connection of secondary windings associated with a single primary. The delta zig-zag connection for 12-phase rectifiers is one example of this method. Twelve-phase operation may also be secured by operating two 6-phase rectifiers in parallel, with the primary of one transformer connected delta and the second in wye. In either case the phase relation between the fundamental-frequency voltages applied to corresponding anodes of the two units is 30 degrees. Theoretically, the lowest-order harmonic in the d-c circuit voltage is then the 12th (720 cycles) appearing as 660 and 780 cycles on the a-c side. Similarly, if it is possible to operate a larger number of 6-phase rectifiers in parallel, and to provide the proper phase displacement between the fundamental-frequency voltages applied to the corresponding anodes of the different rectifiers, the number of phases can be increased, together with the order of the lowest harmonic appearing in the d-c output and a-c supply to the station, as shown in table I.

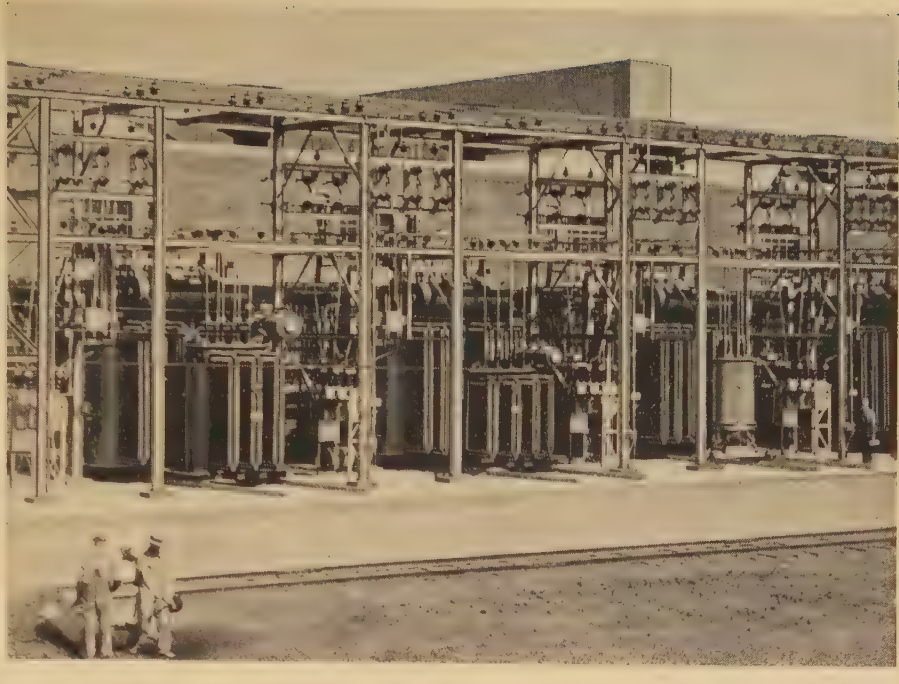


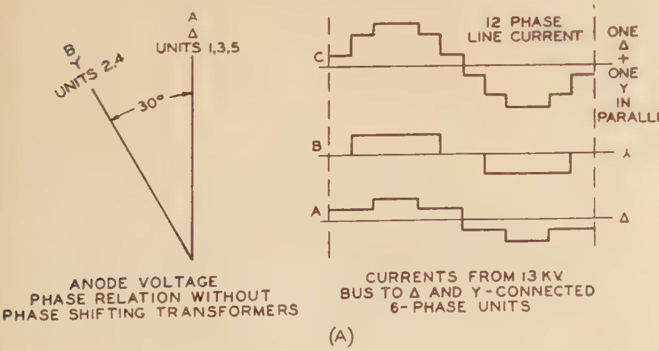
Figure 3. Rectifier transformers, phase-shifting transformers, and reactor

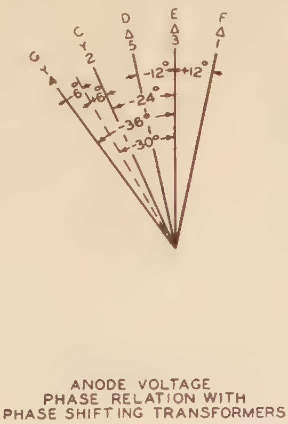
Thirty-Phase Operation at Alcoa and Massena

The rectifiers installed at Alcoa are divided into two stations, each having a total d-c output of 27,500 kw. Each of these stations includes five rectifier transformers, and each transformer, having two double six-phase secondaries, supplies two 12-anode rectifier tanks. All secondaries are connected in double wye with interphase transformers. Each unit (one transformer and two rectifier tanks) is rated at 5,500 kw. Referring to figure 1, in the first station three of the five rectifier transformers have delta-connected primaries, while the primaries of the other two transformers are wye-connected. The second station at Alcoa, as well as the station at Massena, has three units with wye-connected primaries and two with delta-connected primaries. In all three stations four of the units are connected to the supply bus through phase-shifting transformers and one through a reactor.

In figure 1, the connections of the grid-control circuit for regulating the firing of the anodes, and as a consequence the d-c circuit voltage, are shown only for unit 1.

The vector diagram of figure 2*A* shows the 30-degree phase relation between the fundamental-frequency voltages applied to corresponding anodes of a wye-connected and delta-connected unit, and the adjoining curves illustrate the wave forms of the currents between the supply bus and these units without the phase-shifting transformers. The resultant current





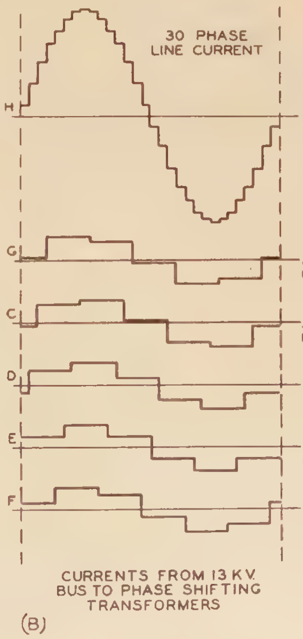


Figure 2. Phase relation between fundamental-frequency voltages applied to corresponding anodes of five units of figure 1 and currents from 13-kv bus to individual units

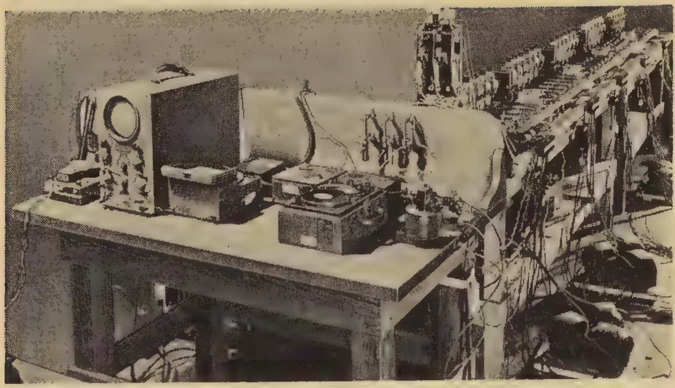


Figure 4. Miniature test set simulating 30-phase system

flowing in the supply circuit, to which these two rectifier units are directly connected, and in case no other converting device is connected to that circuit, is the sum of the currents represented by curves A and B as shown in curve C. (As will be shown later, the wave shape of these currents is not as simple as indicated in this diagram due to other factors, such as resistance, inductance, arc drop, exciting currents of transformers, wave shape of the supply-bus voltage, etc.) The phase-shifting transformers are connected as autotransformers ahead of four of the rectifier transformers, as shown in figure 1. A positive phase shift of 12 degrees is consequently introduced ahead of one of the delta-connected units, with a corresponding negative shift ahead of a second delta unit. Positive and negative phase shifts of six degrees are introduced ahead of the two wye units. As shown in the vector diagram, figure 2B, the fundamental-frequency voltages applied to corresponding anodes of the five units are now 12 degrees apart, and consequently the equivalent of 30-phase operation is obtained, in accordance with the relationships of table I. The wave shapes of the currents between the phase-shifting transformers and rectifier-transformer primaries are the same as those shown for the wye or delta unit of figure 2A, but displaced in phase. The wave shapes of the currents on the line side of the phase-shifting transformers are derived by adding the currents in the various windings of these transformers and are shown in curves C, D, F, and G, of figure 2B. Curve E for the delta-connected unit with a reactor is the same as curve A of figure 2A. The resultant line current is the sum of curves C to G and is represented by curve H in figure 2B. The phase relations, between the anode voltages of the various units are shown by the direction of the secondary windings in figure 1, together with the firing order. The dotted lines of the phase-shifting transformer vectors indicate the supply-bus voltage, and the heavy lines give the relative phases of the voltages applied to the rectifier-transformer primaries.

Different types and sizes of phase-shifting transformers are supplied for 6- and 12-degree phase shift. The transformers for positive and negative phase shift are identical except for some of their internal connections. Both sizes of transformer are designed to have equal reactances of approximately one per cent based on the rating of the rectifier transformer. A three-phase reactor is connected ahead of the unit requiring no phase shift to compensate for the drop in the other units. This reactor was introduced in order to avoid all possible sources of harmonics from unbalances, due to the angle between voltages not being exactly 30 degrees, or the magnitudes of the voltages and the firing period of the anodes not being equal. In the case of the other stations at Alcoa and Massena, where there are three wye-connected and two delta-connected units, the same arrangement is used, except that two wye-connected units are shifted by plus and minus 12 degrees, while the delta units are shifted plus and minus 6 degrees. With this arrangement the anode voltages in the second station at Alcoa are shifted by 6 degrees from those in the first station, and parallel connection of the two stations results in 60-phase operation.

Figure 3 is a view of the transformer yard at Alcoa and shows from left to right the relative size of the phase-shifting transformers for 12 and 6 degrees and of the reactor in comparison with the rectifier transformers.

Test of Miniature 30-Phase Set

The problems to be dealt with in such an involved circuit with several units in parallel cannot be easily and effectively analyzed theoretically except by making many assumptions and neglecting some of the factors. Such an analysis requires a great deal of time and the results are subject to an element of uncertainty, especially in view of the fact that the voltages and currents involved are not of sinusoidal wave shape. For this reason a model 30-phase rectifier test set (see figure 4) was built in order to obtain as quickly as possible the necessary design and operating data and to determine the effectiveness of phase-shifting transformers in connection with these installations.

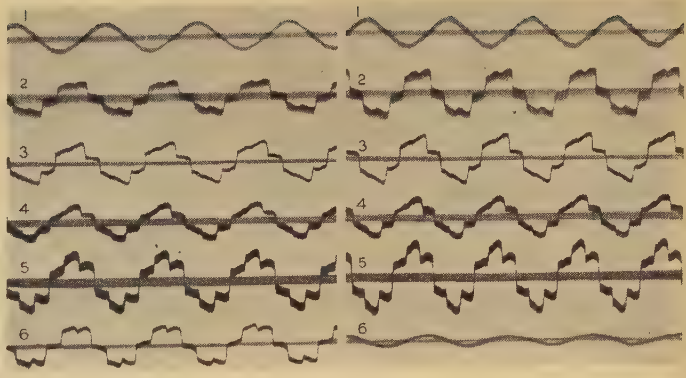


Figure 5. Oscillograms illustrating effect of phase-shifting transformers on currents to each unit in miniature tests

1—Resultant line current
2—Wye unit (−6 degrees shift)
3—Wye unit (+6 degrees shift)
4—Delta unit (−12 degrees shift)
5—Delta unit (no shift)
6—Delta unit (+12 degrees shift)

A—Five units in service
B—Four units in service

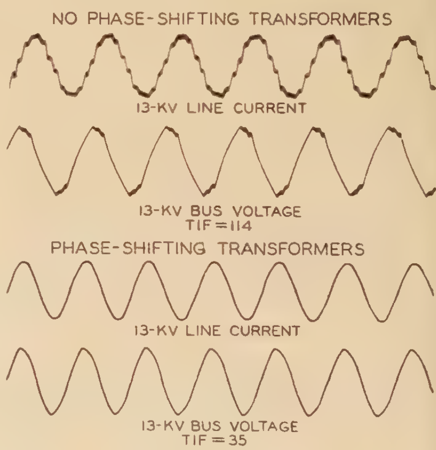


Figure 6. Oscillograms illustrating effect of phase-shifting transformers on wave shape at Alcoa

The set consisted of five units, each unit having a rectifier and a phase-shifting transformer with six grid-controlled

tubes. In other words, each unit of six tubes was comparable to a six-anode rectifier, whereas in the field 12-anode rectifiers are used with two anodes operating in parallel. A polarization voltage simulating the back electromotive force due to the electrolytic cells was provided on the d-c side. The constants or characteristics of the transformers and reactors, although small-scale models were used, were such that representative conditions as to the circulating currents between wye and delta units, resistance and reactance drop, etc., were obtained.

Since very little power was required, the study of the wave shapes with oscillograph and wave-shape analyzer for different system and load characteristics could be carried out very easily and with the greatest convenience. Some of the results obtained with this set are shown in the oscillograms of figure 5*A* and *B*. The lower curves of figure 5*A* show the primary currents in one phase of each of the five units (three delta and two wye), and the top curve is the resultant current of the same phase of the 30-phase system. It will be noted that the latter approaches much more closely a smooth sine wave. A comparison may be made with the curves of figure 2*B* which are arranged in the same order as the oscillographic traces, and the effect of the phase-shifting transformers can be easily analyzed. The trace of the primary current of the last unit is somewhat distorted due to the presence of an abnormally high reactance in the circuit.

Figure 5*B* shows the result of the same setup but with one unit taken out of service. The resultant of the primary current of the four units is somewhat distorted under this condition when compared to the top curve of figure 5*A*. However, the four units still shared the load very satisfactorily. The last trace of figure 5*B* shows the magnetizing current in the primary of the transformer, the cathode of this unit being disconnected. Many other circuit arrangements were studied, taking several units out of service and adding a sixth unit with delta or wye connection to the setup. Furthermore, the influence of delaying the firing of the anodes by means of grid control was investigated and its effect on the shape of the resultant supply bus current observed.

Effectiveness of Phase-Shifting Transformers

According to the relationships of table I, the 30-phase connection should eliminate all harmonics in the a-c supply to the rectifier station below the 29th (1,740 cycles). Complete elimination of these harmonics is not realized in practice, due to slight inequalities in the loads on the rectifier units and in the impedance of the rectifier transformers and associated bus structure, and also on account of difficulties in securing exactly the proper phase relationship between the various anode voltages. However, as indicated in table II, the measured reductions in harmonic current for 30-phase operation compared with straight 6-phase operation, range as high as 90 to 1, with the greatest reductions at the lower frequencies, which are present in the largest magnitudes for 6-phase operation. The $I{\cdot}T$ product,[5] which is an index to the weighted harmonic content of the alternating current, is reduced by as much as 18 to 1 through the use of the phase-shifting transformers.

The improvement in 13-kv line-current and bus-voltage wave shape resulting from the use of the phase shifters is graphically illustrated by the oscillograms of figure 6. The first two traces were obtained immediately after the first rectifier station at Alcoa was placed in operation and before the installation of the phase-shifting transformers. The two lower traces were obtained with the

Table II. Effectiveness of 30-Phase Connection in Reducing Harmonic Currents From 27,500-Kw Rectifier Station Showing Effect of Grid Control†

		"Equivalent 6-Phase Operation" Arithmetic Sum of Harmonic Line Currents in Rectifier Units 1, 2, 3, 4, and 5 (Amperes)			"Equivalent 30-Phase Operation" Vector Sum of Harmonic Line Currents (Total Current to Station) (Amperes)			Effectiveness of 30-Phase Connection as Compared With 6-Phase Operation**		
Harmonic n	Frequency	No Grid Control	Balanced Loads*	5 Per Cent Control	No Grid Control	Balanced Loads*	5 Per Cent Control	No Grid Control	Balanced Loads*	5 Per Cent Control
5	300	266.0	262.0		8.0	5.0		33.0	52.0	
7	420	105.0	101.0		7.9	8.5		13.0	13.0	
11	660	70.5	72.0	78.7	0.79	1.08	2.32	89.0	66.0	34.0
13	780	49.8	47.5	47.5	0.555	0.51	1.7	90.0	94.0	28.0
17	1,020	25.9	26.9	42.5	0.39	0.93	1.9	66.0	29.0	23.0
19	1,140	21.3	23.8	27.1	0.31	0.85	1.4	69.0	28.0	20.0
23	1,380	8.5	9.6	24.7	0.97	0.33	2.6	8.8	29.0	9.4
25	1,500	8.3	10.0	18.2	0.96	1.21	1.4	8.6	8.2	13.0
29‡	1,740	4.96	4.8	13.8	4.85	4.45	13.7	1.02	1.08	1.01
31‡	1,860	4.71	3.9	10.9	4.6	3.6	10.9	1.03	1.08	1.0
35	2,100	4.83			0.57			8.6		
37	2,220	5.03			0.88			5.7		
41	2,460	3.56			0.18			19.7		
43	2,580	3.58			0.17			20.9		
47	2,820	2.29			0.15			15.1		
49	2,940	2.35			0.16			14.4		
53	3,180	1.68			0.41			4.1		
55	3,300	1.65			0.30			5.6		
59‡	3,540	1.29			1.21			1.07		
61‡	3,660	1.23			1.08			1.14		
65	3,900	0.95			0.34			2.85		
67	4,020	1.19			0.45			2.65		
$I{\cdot}T$§		480,000	505,500	659,000	29,600	28,100	78,000	16.2	18.0	8.4
13-kv rectifier bus voltage TIF§					45	38	112			
154-kv bus voltage TIF§					8	10	13			
D-c bus voltage		600	605	575						
Total d-c output current (amperes)		40,000	39,200	35,000						

* Small amount of grid control on certain units to balance d-c output currents.

** Expressed as ratio of arithmetic sum of harmonic currents in individual rectifiers to vector sum of corresponding current.

† These frequencies not suppressed by 30-phase operation.

‡ Measured at Alcoa on station with three delta and two wye units.

§ See reference 5.

same rectifier loads and supply system arrangement after the installation of the phase shifters.

The phase-to-neutral impedances of the 13-kv supply system, looked at from the primaries of the phase-shifting transformers, as calculated from the harmonic voltages and currents for the system arrangement under which the data of table II were obtained, are as follows:

Frequency	Phase-to-Neutral Impedance (Ohms)
660	5.6
780	6.7
1,020	4.2
1,140	3.1
1,380	7.8
1,500	8.3
1,740	13.6
1,860	11.1

The commutating reactance of the rectifier transformers is approximately six per cent.

Effect of Grid Control on 30-Phase Operation

Included in table II are the results of tests to determine the effect on the a-c wave shape of reducing the d-c bus voltage by the use of grid control.[2,6] The use of only a small amount of control on certain units to balance the d-c load among the units makes no substantial change in the over-all effectiveness of the phase-shifting transformers. However, with grid control used to reduce the d-c bus voltage in the order of five per cent, the over-all effectiveness of the 30-phase arrangement is somewhat impaired, as indicated by an increase of about 3 to 1 in the $I \cdot T$ product. Even under this condition, the 30-phase arrangement is about eight times better than straight six-phase operation with the same amount of grid control, and the reductions at four important frequencies (660, 780, 1,020, and 1,140 cycles) are 20 to 1 or more.

Vector Relations Between Harmonic Line Currents

The effectiveness of the 30-phase connection in reducing the harmonics out of the rectifier station depends upon the balance of five nearly equal currents in the proper phase relation. This is illustrated in figure 7*A* which shows the measured vector relations between the 780-cycle line currents to the five rectifier units of figure 1. These currents were measured on the line side of the phase-shifting transformers. The phase angles were obtained from measurements of sums and differences of the harmonic voltage drops across inductive shunts in the secondaries of the current transformers associated with each unit. It is evident from the diagram that the five vectors are nearly equal and approximately 72 degrees apart. The resultant of the five vectors is also shown. The reduction factor of 89.5 is the ratio of the arithmetic sum of the five currents to the vector sum or the resultant current.

Since 780 cycles (13th harmonic) appears in the a-c supply as a result of the 12th harmonic in the d-c wave, the phase shift of the various 780-cycle currents from that in unit 3 (taken as reference) should be 12 times the fundamental-frequency shift introduced by the phase-shifting transformers. The derivation of the fundamental-frequency angles from the measured angles is shown in figure 7*A*. The derived values are fairly close to the theoretical 6- and 12-degree shifts.

A similar diagram for the 37th harmonic is shown in figure 7*B*. In this case the phase shift is 36 times that at the fundamental frequency. The fundamental-frequency shifts derived from the measured angles are about the same as those derived from the 780-cycle diagram. However, the effects of the small deviations from the correct shifts of 12 and 6 degrees tend to become greater for the higher-order harmonics, and the angles between the five vectors in figure 7*B* no longer closely approximate 72 degrees. The reduction factor is only 5.7 compared with 89.5 at 780 cycles.

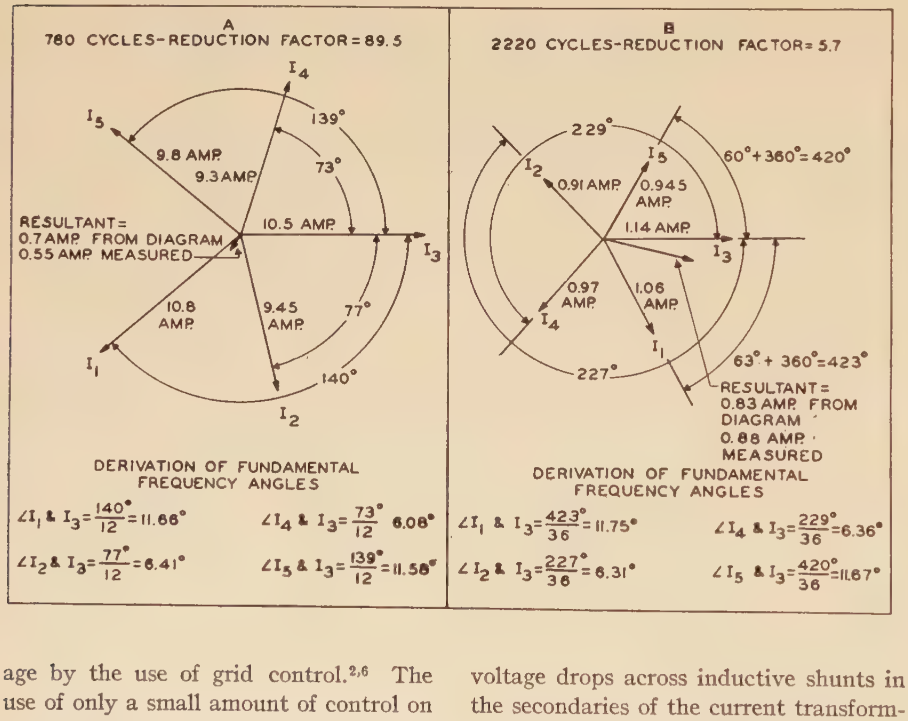


Figure 7. Measured vector relations between harmonic line currents to five rectifiers equipped with phase-shifting transformers for 30-phase operation as shown in figure 1

Table III. Effect of "Balanced" and "Unbalanced" Rectifier Operation†

Ratio of Harmonic Currents With 6-Phase Operation to Those Measured With 30-Phase Operation

Frequency	Five Units in Parallel "Balanced Rectifiers"*	Four Units in Parallel*
300	51.5	5.9
420	27.0	4.5
660	43.7	3.7
780	35.7	3.8
1,020	29.0	3.0
1,140	42.0	3.9
1,380	22.9	2.2
1,500	28.2	2.7
1,740‡	0.95	1.01
1,860‡	0.92	1.05
2,100	6.2	
2,220	5.8	
2,460	23.5	
2,580	38.2	
2,820	24.0	
2,940	16.2	
3,180	6.3	
3,300	3.9	
3,540‡	1.12	
3,660‡	1.19	
3,900	3.5	
4,020	3.8	
$I \cdot T$ (ratio)	15.9	3.2
$I \cdot T$ (6 phase) magnitude	449,000	330,000
$I \cdot T$ (30 phase) magnitude	28,300	104,000
Voltage TIF (13-kv rectifier bus)	29.0	69.0

† Measured at Massena on 27,500-kw station with three wye and two delta units.

‡ These frequencies not suppressed by 30-phase operation.

* Same total d-c load in each case.

Table IV. Effect of Phase-Shifting Transformers on Supply-System Voltage Wave Shape and Telephone Circuit Noise (for 27,500-Kw Station in Operation at Alcoa)

	Rectifiers Off	Five Units* No Phase Shifters	Five Units Phase Shifters**
Power System A	Voltage TIF		
Alcoa 13-kv rectifier bus	10	176	40
Alcoa 154-kv bus	10	77	15
Location 1 on 154 kv	9	64	7
2 on 154 kv	12	118	13
3 on 154 kv	29	480	34
4 on 154 kv	16	84	14
	Maximum Noise on Exposed Toll Circuits		
Decibels above reference noise	37	57	37
Noise units	500	5,000	500
Power System B	Voltage TIF		
Alcoa 13-kv rectifier bus	10	79	14
Alcoa 120-kv bus	10	51	10
Location 5 on 120 kv	15	56	21
6 on 120 kv	9	23	12
7 on 66 kv	14	33	24
	Maximum Noise on Exposed Toll Circuits		
Decibels above reference noise	32	44	35
Noise units	280	1,100	400
Power System C	Voltage TIF		
Alcoa 13-kv rectifier bus	10	137	
Alcoa 154-kv bus	14	233	16
	Maximum Noise on Aluminum Company Telephone Circuits		
Decibels above reference noise	42	73.5	42
Noise units	900	33,000	900

* Equivalent to one 12-phase rectifier of 22,000 kw and one 6-phase rectifier of 5,500 kw in parallel.

** "Balanced operation."

"Balanced" and "Unbalanced" Operation

From the vector diagrams of figure 7 it may be seen that the effectiveness of the 30-phase method of operation is impaired if one of the units is shut down. If the load on the four remaining units is unchanged, the resultant harmonic current at the suppressed frequencies will be equal to the current which was supplied by the unit which was shut down, or the reduction from straight six-phase operation will be four to one. This reduction is approximately realized in practice as shown by the ratios in the last column of table III. The reduction factor for the $I \cdot T$ product is about three to one.

A comparison of the data for "balanced" operation in tables II and III shows that the phase-shifting transformers are about equally effective whether applied to a station comprising three delta and two wye units, or three wye and two delta units.

Supply-System Wave Shape and Telephone-Circuit Noise

The previous comparisons have been made on the basis of the improvement effected by 30-phase operation of the rectifiers compared with straight 6-phase operation. Actually, before the installation of the phase-shifting transformers, four of the units in the first station at Alcoa made up two 12-phase rectifiers, with one extra 6-phase unit. This method of operation made substantial reductions (as compared to straight 6-phase operation) in the harmonic line currents at 300, 420, 1,020, 1,140 cycles, etc., while accomplishing no reduction at 660, 780, 1,380, 1,500 cycles, etc. The wave-shape and noise tests which indicated the necessity for further reductions in the harmonics were made with this arrangement, and under a variety of supply-system conditions presenting different system impedances as viewed from the rectifiers. To indicate the improvement in wave shape and noise conditions accomplished by the installation of the phase-shifting transformers, the summary of table IV is included. The maximum noise values on exposed telephone toll circuits are included merely to indicate the order of improvement effected on a large number of circuits when the phase shifters were installed.

Table V. Effect of 30-Phase Rectifier Operation on Voltage TIF of Supply Systems to Massena 27,500-Kw Rectifier

Circuit	Rectifiers Off	Balanced Rectifiers	One Unit (No. 3) Out of Service
Power condition (a)			
Massena rectifier 13-kv bus	12.1	28.8	69
Massena 110-kv bus	14.8	15.8	21
Location 1—13-kv bus	20.7	20.6	22.8
Location 2	27*	24*	32*
Power condition (b)			
Massena rectifier 13-kv bus	9.1	48	75
Massena 110-kv bus	14.1	14.7	15
Location 2	28.8*	32.5*	35.7*

* 1,500-cycle component from 450-horsepower synchronous motor on motor generator set controlled the voltage TIF at location 2. TIF observed with motor off, but with balanced loads on the rectifiers, was 11.

Tests made at Massena following the installation of the 27,500-kw (five-unit) station equipped with phase-shifting transformers indicated that the rectifiers had practically no effect on the wave shape of the 110-kv supply system under the "balanced" operating condition, and a relatively small effect when one unit was out of service, as indicated in table V.

Final tests were made at Alcoa after the completion of the second station and with phase-shifting transformers installed ahead of all ten units to provide 60-phase operation. The results of these tests under three power conditions are shown in table VI and indicate that voltage-wave-shape conditions under balanced operation compare favorably with those existing before the rectifier station was installed. The effects of grid control and of "unbalanced" operation with one unit out of service are also shown in table VI.

Conclusion

As demonstrated in the case of these large rectifier installations, the introduction of autotransformers as phase shifters offers a very attractive means of reducing harmonic components which otherwise would be outstanding where multiunit rectifiers are involved. In situations of

Table VI. Power-System Influence Measured With 55,000-Kw 60-Phase Rectifier Operating at Alcoa

	Voltage TIF 13-Kv Rectifier Bus	Voltage TIF 154-Kv Bus	Voltage TIF 120-Kv Bus	Total 13-Kv I·T Product
Power condition a-2				
Rectifiers off	10.0	9.0	10.0	
Balanced (no control)	14.3	11.0	4.5	37,000
Balanced (5 per cent control)	14.5	10.2		48,000
Unbalanced* (no control)	37.0	40.5	12.6	154,000
Power condition a-1				
Rectifiers off	10.0	9.0		
Balanced (no control)	28.2	12.8		42,000
Balanced (2 per cent control)	31.5	19.2		45,000
Unbalanced* (no control)	67.0	37.0		126,000
Power condition a-3				
Rectifiers off	10.0	14.0		
Balanced (no control)	15.2	11.9		43,500
Balanced (5 per cent control)	17.4	11.6		65,000
Unbalanced* (no control)	40.3	41.5		153,000

* One unit shut down—nine units operating.

this character, this method of improving wave-shape conditions has proved not only effective but also simpler and more economical than the application of filtering devices, usually consisting of a combination of reactors and capacitors, which have been used to some extent with satisfactory results in smaller rectifier installations.

The application of phase shifters is by no means limited to the present arrangement, but can be adapted to a variety of conditions. For instance, in case four units (with four or eight tanks), instead of five units as in the above stations, would suffice to meet the required load, a 24-phase system could be arranged by using one phase shifter, giving a relative phase displacement of 15 degrees, in connection with two rectifier groups, each consisting of a transformer with a wye and with a delta connected primary. The same result could be secured by using two identical phase shifters for plus and minus 7.5 degrees. In case three units (with three or six tanks) would take care of the required load, or if larger rectifier units could be built to meet the load of the stations described above, an arrangement could be used comprising three 12-phase rectifier units, one shifted plus 10 degrees and another minus 10 degrees, resulting in 36-phase operation. Such an arrangement would appear to offer some advantage over the present 30-phase system, as it would require only one type of rectifier transformer, although of a more complicated construction, and one design of phase-shifting transformer. The 12-phase system could be obtained with one wye and one delta 6-phase transformer as one unit, or the conventional 12-phase with quadruple secondary. This would simplify the problems of design, installation, and eventual replacement, and should result in an even better wave shape than the 30-phase arrangement. However, the flexibility of the station would be somewhat impaired due to the smaller number of units. Other arrangements may, of course, be used to suit the particular requirements of each case. When the supply-system impedance conditions are such that the influence is materially affected by those harmonic components which are unsuppressed with the particular arrangement employed, it should be relatively simple to reduce these components by means of selective devices.

The solution of the wave shape and noise problems presented by these large rectifier installations is an illustration of the results which can be achieved by co-operation between the electrical manufacturer, the purchaser of electrical equipment, the power-supply companies, and the communication companies. It is expected that the experience gained during this study will be valuable in the design and installation of future large rectifier stations.

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1. Effects of Rectifiers on Power System Wave Shape, **Blye and Kent.** AIEE Transactions, 1934, page 54.

2. Current and Voltage Wave Shape of Mercury Arc Rectifiers, **Brown and Smith.** AIEE Transactions, volume 52, December 1933.

3. Rectifiers Adopted for American Aluminum, **Bohn and Gutzwiller.** *Electrical World*, December 3, 1938.

4. Mercury Arc Power Rectifiers (a book), **Marti and Winograd.** McGraw-Hill, 1930, chapter 6.

5. Measurement of Telephone Noise and Power Wave Shape, **Barstow, Blye, and Kent.** AIEE Transactions, volume 54, 1935, page 1307.

6. Grid Control of Mercury Arc Rectifiers, **O. K. Marti.** *Electrical World*, volume 102, October 14, 1933, pages 507–09.

Voltage Control of Vapor Rectifiers, **D. Journeaux.** Electrical Engineering (AIEE Transactions), page 976, 1934.

Discussion

F. O. Stebbins (General Electric Company, Schenectady, N. Y.): This paper presents an entirely adequate solution of this particular communication-circuit noise-level problem and because of its complete form and the factual data contained therein is a valuable contribution to the literature on this subject.

Apparently the noise level at rated kilowatt load, with all units operating (at approximately equal kilowatt load per unit) is well below the minimum acceptable values. It may be assumed that with the same kilowatt load imposed on four units instead of five or nine tanks instead of ten that the noise levels in the high-voltage bus materially affecting communication circuits were still within acceptable limits.

In studying this problem was it possible to (1) establish some minimum acceptable noise level as an objective; (2) determine whether the 13-kv or the high-voltage (110 or 154 kv) lines would govern permissible noise levels?

Due to the very nature of electrochemical operations all equipment must be capable of carrying rated load 24 hours per day, 365 days per year. Hence the determination of an acceptable minimum noise level under the least favorable operating conditions (such as normal kilowatt load imposed on four instead of five units or nine instead of ten tanks) is most important, and may have a material influence on station layouts, provisions for spare capacity, etc.

Local conditions, at the point of installation, such as (*a*) the capacity and extent of a-c power supply, (*b*) interconnection of this system with other systems, (*c*) exposure of open-wire main-trunk-line communication systems to the power supply, (*d*) the number of high-voltage transformations in the complete system have an important effect on the solution of this noise-level problem.

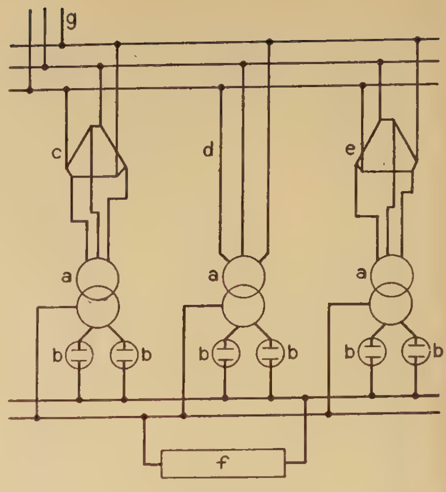

Figure 1. Large rectifier plant with 36-phase connection

a—12-phase transformers of identical construction; output 8,000 kw each
b—Two 5,000-ampere 800-volt rectifiers per transformer
c—Phase shift transformer for plus ten degrees
d—Without phase-shift transformer
e—Phase-shift transformer for minus ten degrees
f—Load
g—Supply lines

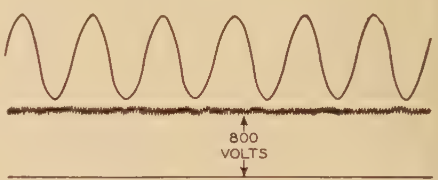

Figure 2. 36-phase connection obtained by parallel operation of three 12-phase transformers, each for 10,000 amperes, 800 volts

Common primary current of the three rectifier transformers

As examples the 60,000-kw station of the Consolidated Mining and Smelting Company at Trail, B. C., and the 54,000-kw station of the Aluminum Company of Canada do not at present require equipment to improve the wave shape of the power supply. All of these factors may be studied prior to installation and an approximate solution attained.

The harmonic reductions the authors obtained with the 30-phase group seem to approach maximum values approximately halfway between the frequencies that the 30-phase group does not suppress. That is, these reductions increase to maximum values at 13th and 43rd harmonic frequencies, but are zero at 29th, 31st, 59th and 61st harmonic frequencies, etc. Did the authors find that this same characteristic applied also to the 60-phase group, and the reductions in the harmonics approach a maximum at approximately 29th harmonic frequencies? Also how did the harmonic reductions of the 60-phase group compare with those obtained with the 30-phase group?

We note that the authors built and tested a miniature 30-phase rectifier in their fac-

tory and made a study of the effect of unbalanced 30-phase operation by shutting down one unit in a 30-phase group. The poorest wave shapes obtained with unbalanced operation, which are shown on the oscillogram taken in the factory, are made evident later in the rectifier installations at Alcoa and Massena, where unbalanced operation increased the voltage TIF on the 13-kv station bus, approximately two to one.

We would like to know whether the authors' tests showed that the large harmonic reductions obtained on the a-c side of the 30-phase rectifier also were found to exist on the d-c side of the rectifier. Did these reductions increase to maximum values at frequencies halfway between the 30th and 60th harmonic frequencies, as they did on the a-c side of the rectifier?

It has been found that odd harmonics in the a-c supply voltage wave to a rectifier come through to the d-c side of the rectifier as even harmonics of approximately the same percentage value. Did the authors learn whether a 30-phase or a 60-phase group will tend to reduce the percentage values of the harmonics in the d-c output voltage, produced by harmonics in the a-c supply voltage?

Have the authors reached any conclusions regarding the economic limit of filtering equipment, that is the maximum kilowatt rating of a station at which the filter is a more economical solution to the wave-shape problem than the phase-shifting autotransformer?

E. V. DeBlieux (General Electric Company, Pittsfield, Mass.): The authors of the paper have made a valuable contribution to rectifier operating experience in reporting the results of tests of the Massena and Alcoa installations. These tests demonstrate that wave-shape distortion of rectifier installations can be reduced to acceptable values by phase multiplication.

The required kilowatt output of the station, purchaser's specifications covering the number of operating units, and operating requirements as to spare capacity, will determine the number of units (transformer and associated rectifiers) in a given station. At the present time the units must operate either in 6-phase or 12-phase relationship to the supply system. These factors will determine what can be done by way of phase multiplication to minimize TIF. I believe that there is little advantage in going to more than 36, or possibly 48 phases, because the higher harmonics are a small item in the TIF, extreme accuracy of phase shift is required to eliminate these higher harmonics (see figure 7*b* of the paper), and also unless the output is very large it is not economical to divide the installation into the large number of units required.

The authors state that due to various factors, complete elimination of certain harmonics was not realized. Were any tests made to determine whether or not it would be possible to improve the harmonic elimination by unequally dividing the load or by altering the phase shift between units? Figures 1 and 2 of this discussion are a connection diagram and an oscillogram of a German installation that consisted of several 24,000-kw 36-phase sets using a connection similar to that at Alcoa. The oscillogram shows the same excellent line-current wave shape as figure 6 of the subject paper. In the German installation reactors were connected in the rectifier cathode lines to limit the harmonic currents that circulate between rectifiers and transformer secondaries as a result of the phase displacement between units. Did the authors of the paper take oscillograms of anode current or other measurements to determine the magnitude of the circulating harmonic currents in their installation?

S. A. Flemister (Southern Bell Telephone and Telegraph Company, Atlanta, Ga.): The paper by Doctor Marti and Mr. Taylor contains much interesting information regarding the many important electrical features of a large mercury-arc-rectifier installation such as that at the plant of the Aluminum Company of America at Alcoa, Tenn. Of most interest and concern to telephone engineers are, of course, those features relating to the harmonics impressed by the rectifiers on the connected a-c power-supply network, since it is through the propagation of these harmonics over the connected high-voltage transmission lines and thence over the urban and rural distribution systems connected therewith that the noise-influence problem may become important.

As it was my good fortune to participate in the tests and analyses made in connection with the Alcoa installation, the paper under discussion is most interesting to me. While the paper covers rather completely

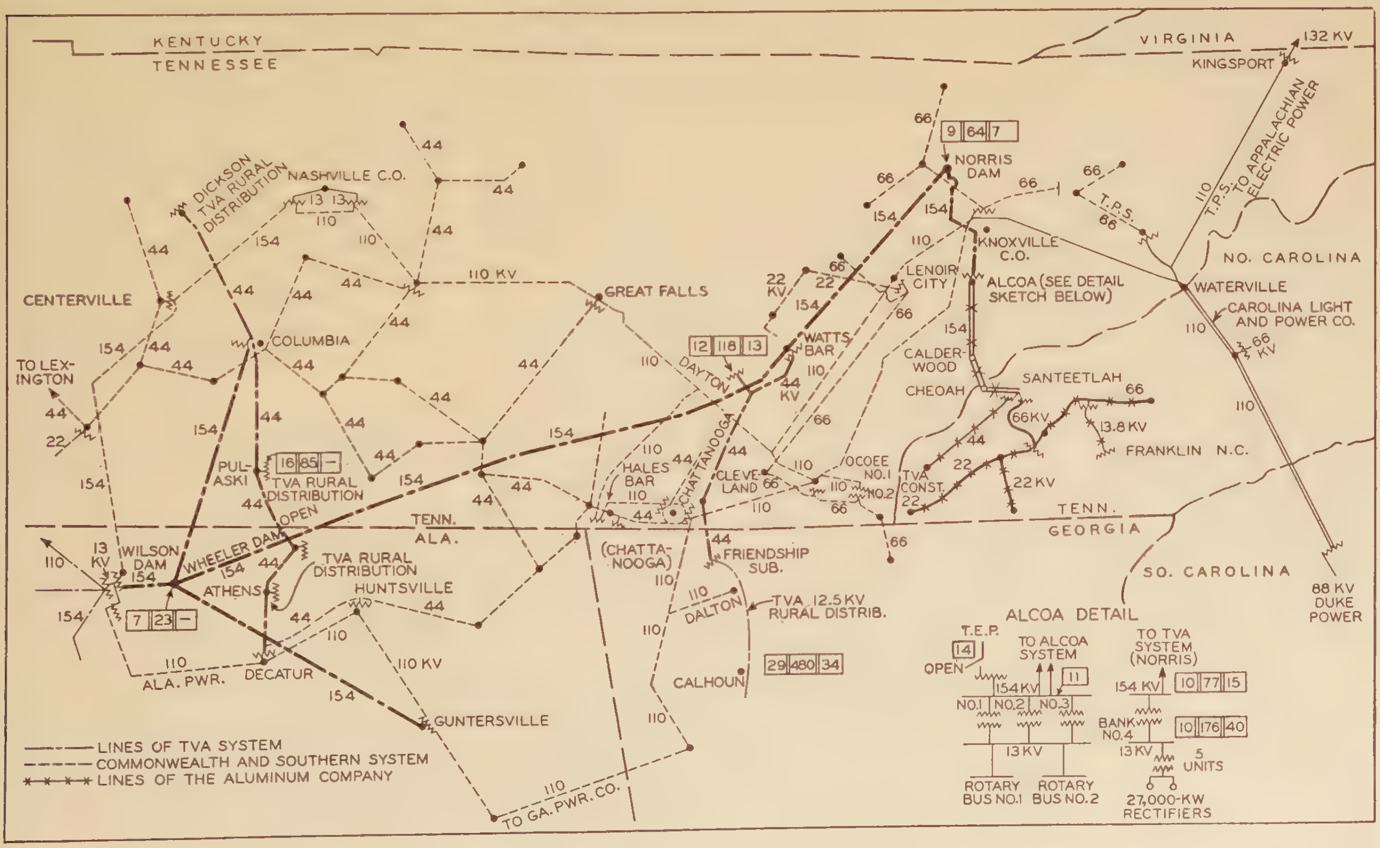

Figure 3. Voltage telephone influence factors measured at various points

27,000 kw of rectifiers supplied from TVA only

The value in the left-hand side of the box at a given location shows the voltage telephone influence factor without rectifiers on system. The value in the center of box shows the voltage TIF with rectifiers and without phase-shifting transformers. The value in the right-hand side of box shows the voltage TIF with rectifiers and with phase-shifting transformers

the technical aspects of the problem, I believe it will also be of interest to describe the scope of the problem and the co-operative arrangements which so facilitated the testing work and the ultimate solution.

To illustrate the scope of the problem from the operating standpoint, figure 3 of this discussion has been prepared to show the wide geographical area and the extensive connected transmission-line network involved. By reference to the figure, it may be seen that the area included large parts of the states of North Carolina, Georgia, Alabama, and Tennessee, which are served by a part or all of the transmission-line systems of the Carolina Power and Light Company, the Nantahala Power Company (owned by the Aluminum Company), the Tennessee Public Service Company, the Tennessee Valley Authority, the Tennessee Electric Power Company, the Alabama Power Company, and the Aluminum Company of America. As can be appreciated, in addition to the network of transmission lines shown, there were extensive connected urban and rural distribution networks, many of which were involved in inductive exposures to the circuits of the telephone plant.

Based on experience with other (smaller) rectifier installations and on the studies made by the Joint Subcommittee on Development and Research of the Edison Electric Institute and Bell Telephone System, it seemed quite probable from the beginning, that a rectifier installation of the magnitude contemplated would result in widespread and important increases in power-system influence and in the noise on telephone systems exposed to the circuits of the connected power network. In view of this, the problem was discussed at an early date with all of the power organizations whose systems might be affected as well as with the Aluminum Company and the Allis-Chalmers Company. All of these organizations were very interested and expressed their desire to do whatever they could to find the best possible solution. This wholehearted interest and co-operation continued throughout the investigation.

In deciding upon a test program and procedure, it was felt that the program should include not only tests at Alcoa, but simultaneous tests at strategic outlying points in the area served by the power networks connected directly or indirectly to the bus at Alcoa. Accordingly, single-line diagrams of the power systems involved were studied and the field-test locations selected. These locations were carefully selected so that the pertinent data could be obtained and a suitable test schedule worked out to fit in with switching arrangements, etc., necessary for the tests at Alcoa. As the testing program progressed, it became desirable to add a few field locations to those originally designated.

The paper under discussion covers the testing and test results at Alcoa quite fully. However, little is said concerning the correlated tests at the field locations which were made simultaneously with certain of the Alcoa tests. The chief purpose of these field tests was to determine by the manner in which the various harmonics were propagated from Alcoa, the magnitude and extent of the changes in the power-line influence with the rectifiers connected to the different power systems under normal and probable emergency power operating conditions. Tests at these locations were all made with instruments of the indicating type and consisted of voltage-wave analyses, noise tests on selected representative telephone circuits, and measurements of the telephone influence factor (TIF).

As an indication of the extent of propagation of the harmonic voltages arising in the rectifiers, the measured TIF values at several locations are shown in the figure for one of the power operating arrangements tested. This is the condition of the TVA system only supplying 27,000 kw of rectifiers, which represented half the station capacity. Three values of measured TIF are shown in boxes at the selected locations for the TVA system. In the box to the left is shown the reference value of TIF measured with no rectifier load connected to the power system. The value in the middle shows the measured TIF with the rectifiers connected to the system but with the phase-shifting transformers out. In the right of the box is shown the TIF value with the rectifiers supplied through the phase-shifting transformers.

The final solution adopted was, as discussed in the paper, accomplished by the provision of specially designed phase-shifting transformers. These particular transformers are, as indicated by the data shown on the figure, amazingly effective in reducing the harmonics which would otherwise be impressed on the connected power network. A satisfactory reduction might have been accomplished through other means, such as the use of filters, etc. However, had filters been employed, they probably would have been more costly and their effectiveness would have been dependent upon keeping the power-system impedance nearly the same as that assumed in the design of the filters. This restriction would, of course, have been very undesirable from the power operating viewpoint. The use of the phase-shifting transformers has provided a very satisfactory method of harmonic suppression and their action in this respect is independent of changes in the connected power network, a feature which is, of course, most desirable.

This whole investigation seems to me to be a rather striking illustration of what can be accomplished in a very complex (and at times almost discouraging) problem when it is approached by a group of engineers working in close co-operation and interested only in determining the facts and in working out a solution based on these facts. There is no need and not enough time to recount in detail the part played by each organization because any one can see that only by the closest co-ordination between the Aluminum Company on the one hand and the power organizations on the other could it be possible to carry out tests over such a wide area and under so many power-system arrangements and operating conditions smoothly and efficiently. I cannot refrain also from paying tribute to the people who conceived the idea of the phase-shifting transformers and to those who actually designed and built them.

The Southern Bell Telephone and Telegraph Company and the long-lines department of the American Telephone and Telegraph Company were assisted in the conduct of the field tests and in the analysis of the results by engineers from the headquarters organization of the American Telephone and Telegraph Company and Bell Telephone Laboratories in New York. The Western Union Telegraph Company and the Southern Railway, which operate communication facilities in the area, were kept in close touch with the study.

O. K. Marti and **T. A. Taylor:** Mr. Flemister's discussion supplements the data in the paper and emphasizes the scope of the co-ordination problem and the co-operative arrangements employed in its solution.

In answer to the question of Mr. DeBlieux, no tests were made to determine the effect on harmonic reduction of unequally dividing the load or altering the phase shift between units. An effort was made to keep the loads balanced and no provision was available on the phase-shifting transformer for changing the phase shift. While some improvement might be made by these changes, neither change seems practicable in commercial operation. No measurements were made of the magnitudes of the circulating harmonic currents during the joint study. However, some data were secured by the Allis-Chalmers Company and will probably be included in another paper covering additional aspects of this installation.

In answer to Mr. Stebbins' question, there is, of course, no practical method of setting up definite limits for noise or power-system influence. In this particular case the power-system influence and the noise levels on exposed telephone circuits before the rectifiers were placed in operation were taken as the primary objective in determining the desirable reductions in the harmonics. This objective was fully met under conditions of balanced operation of the station, although some increases in influence and noise were noted with unbalanced operation. Since the principal exposures were to power distribution circuits supplied from the high-voltage systems (110 and 154 kv), and there was relatively little exposure to the 13-kv system at Alcoa, the wave shape of the high-voltage system was assumed to be controlling in the study. The authors agree that many factors such as those mentioned will enter into the solution of such a problem.

Detailed measurements were not made on the 60-phase installation, so data are not at hand to make the comparison requested. However, the over-all measurements indicated that the 60-phase connection was at least as satisfactory as the 30-phase connection with respect to harmonic reductions.

No co-operative tests were made on the wave shape of the d-c end of this installation, since no noise problem was involved. Theoretical considerations indicate that substantial reductions would be expected in the harmonics on the d-c output as the number of phases is increased. This is particularly important from the standpoint of the use of the larger number of phases in connection with d-c transmission and merits further study.

No definite conclusions regarding the economic limit of filtering equipment have been reached. In general, it appears that the multiphase connection will be restricted to the larger installations, where all units are operated in parallel at constant load, while the various filter arrangements may be more economically applied to the smaller installations.

Lightning Investigation on Transmission Lines—VII

W. W. LEWIS
FELLOW AIEE

C. M. FOUST
MEMBER AIEE

THE lightning investigation reported in previous papers of this series was continued in 1937 and 1938, with the following power companies participating:

Pennsylvania Power and Light Company
Ebasco Services, Inc.
Appalachian Electric Power Company
American Gas and Electric Company
Consumers Power Company

The following companies also co-operated by furnishing pertinent information:

Pennsylvania Water and Power Company
Philadelphia Electric Company
Public Service Electric and Gas Company

Work was confined mainly to a study of magnitude and distribution of current in tower members, overhead ground wires, conductors and counterpoise wires. All readings were taken by means of magnetic links.[1] The present paper constitutes a progress report on certain features of the investigation.

Current in Towers and Strokes

In the immediately preceding paper of this series,[2] cumulative curves were shown of tower and probable stroke current, involving 358 strokes on four systems, during the years 1933, 1934, and 1935.

Figure 1 of the present paper shows similar curves for 734 strokes, on seven lines ranging from 66 to 220 kv, during the four years from 1933 to 1936 inclusive. The shapes of these curves do not differ greatly from the previous curves.

In working up the data for figure 1, tower currents were found by adding the currents in the four legs and neglecting any currents that might flow in the diagonal members or braces. Stroke currents were found by adding currents in all towers affected by the stroke. As ordinates the average of each 10,000-ampere range has been plotted.

In 1937 and 1938 a number of installations were made in which magnetic links were placed on cross members or braces in addition to the corner legs. It was found that the cross members carried from 30 to 100 per cent as much current as the legs, depending on how symmetrical the counterpoise arrangement was with respect to the tower legs. However, no currents were measured which indicated tower or stroke currents in excess of those shown on figure 1.

Occasional questions have been raised as to the validity of the method of obtaining stroke current by adding currents in adjacent towers which appeared to be affected by the same lightning discharge. Accordingly measurements obtained near the tower top and before current subdivision had taken place have been analyzed to show direct-stroke currents. These records were obtained on tower-top lightning rods and overhead ground wires and are summarized in table I.

This table includes some 80 records obtained over several years operation and on four different lines. The percentage figures from table I have been plotted on figure 2 against the average of each 10,000-ampere range. For comparison the stroke-current curve from figure 1 has been reproduced on figure 2.

The direct measurement in rods and ground wires shows a higher percentage of strokes in the low-current range and a lower percentage of strokes in the high-current range. The higher percentage of low-current strokes is not due to current sensitivity of the measurement stations because considering division of current, the rod and ground wire stations recorded down to about the same current level as the tower stations. Possibly in interpreting stroke currents by addition, some low-current records which were considered portions from another stroke should have been classified as direct strokes. The lower percentage of high-current strokes obtained through rod and ground-wire measurements results from two circumstances: A number of currents extended above the upper limit of range of the measurement station. Also, it is quite reasonable that in adding up tower currents to obtain stroke currents a few excessively high records were obtained in assigning adjacent tower currents to a single stroke when in fact more than one stroke occurred. The agreement between the different methods of evaluating the stroke current is fairly good. For practical purposes, an upper limit of current somewhere between the two curves, say 150,000 amperes, may be chosen.

Lightning Currents in Line Structures

Comparing surge currents and surge-current summations in various parts of the line structure is frequently disappointing unless attention is given to a number of possible current combinations. An analysis has been made of 42 sets of records wherein currents flowing up the tower structure could be compared with corresponding currents leaving the tower top through overhead ground wires and lightning rods.

A direct comparison of "inward" with "outward" flowing currents is possible if the tower top is considered as the summa-

Table I. Range of Direct-Stroke Currents

Range of Current (Amperes)	Lightning Rods: Number Strokes in Range	Lightning Rods: Per Cent of Number Exceeding Current Range	Overhead Ground Wires: Number Strokes in Range	Overhead Ground Wires: Per Cent of Number Exceeding Current Range
Below 10,000	0	100	6	88
10,001– 20,000	4	87	4	80
20,001– 30,000	3	77	6	68
30,001– 40,000	7	53	7	54
40,001– 50,000	9	23	13	28
50,001– 60,000	3	13	4	20
60,001– 70,000	1	10	4	12
70,001– 80,000	3	0	1	10
80,001– 90,000			1	8
90,001–100,000			2	4
100,001–110,000			2	0
Total	30		50	

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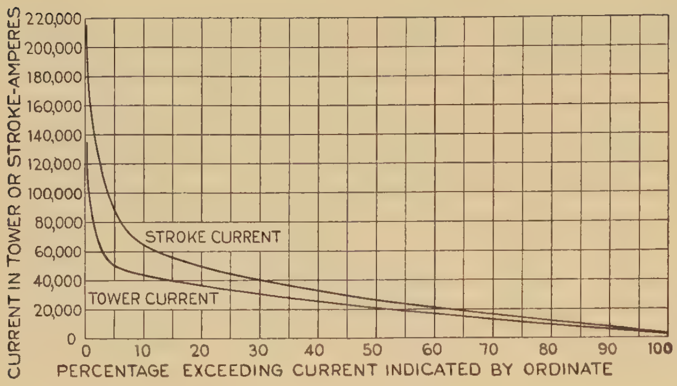
W. W. LEWIS is in the engineering division of the central-station department and C. M. FOUST is in the general engineering laboratory, General Electric Company, Schenectady, N. Y.

1. For all numbered references, see list at end of paper.



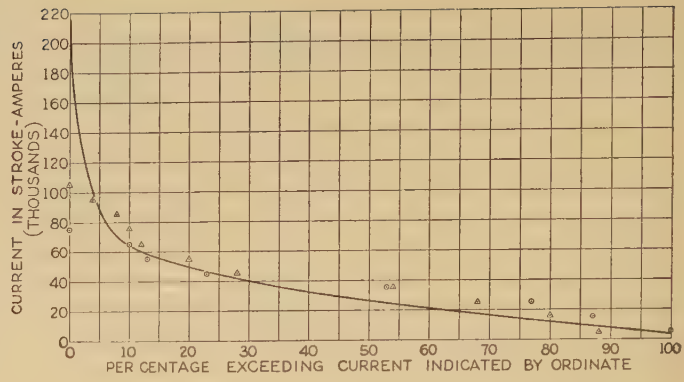


Figure 1. Cumulative curves of tower and probable stroke currents from 734 strokes occurring during the years 1933 to 1936 inclusive on the Wallenpaupack-Siegfried, Glenlyn-Roanoke, Safe Harbor-Westport-Takoma, Philadelphia-Delaware state line, Safe Harbor-Perryville, Holtwood-Coatesville and Holtwood-York transmission lines, ranging in voltage from 66 to 230 kv

tion point, and current polarities or current direction as indicated by the magnetic links are noted.

If currents are combined by simple algebraic addition a wide range of results is obtained. "Inward" and "outward" currents agree in about 25 per cent of the 42 cases, "inward" currents are in excess of "outward" in about 50 per cent and "outward" in excess of "inward" in about 25 per cent of all cases.

In table II are shown specimen records wherein "inward" and "outward" current values agree within plus or minus ten per cent.

In all of the cases of table II, current flowing along the ground wire or wires was joined by current flowing up the tower, and in each case current flowed into a stroke to a ground wire.

The most common case is one in which upward-flowing tower current exceeds the outward flowing current at the tower top. A number of specimens of such records is given in table III.

The first two cases are associated together because the towers are adjacent and the stroke was to a ground wire between them. Records indicate another low-current stroke to have occurred two tower spans away during the same period of exposure of these magnetic links.

For the third item where the tower-cage current was 69,630 amperes, the parallel counterpoise wire fed some 30,700 amperes into the tower base. As this counterpoise wire was connected only on one side of the tower the cross-members' currents were very high, exceeding the leg currents in magnitude. In this case, that of a two-ground-wire line, ground-wire currents flowed past the tower top in one direction on one overhead ground wire and past the tower top in the opposite direction on the other ground wire. Indications are that two strokes were present, one to the structure itself and one nearby to one of the overhead ground wires.

The fourth case is again one in which the upward current in the tower when increased by the inward flowing current in the ground wire, exceeded the outward-flowing ground-wire current. Here, however, the 70,000-ampere outward-flowing current saturated the magnetic link in the inner position leaving only the outer link available for measurement purposes. Some degree of oscillation in this current or a low magnitude reversed current would readily reduce an 82,000-ampere single-link indication to 70,000 amperes.

The fifth item, a 57,000-ampere stroke to a lightning rod, included three ground-wire currents flowing inward toward the tower top. The reading on the fourth ground wire was wiped out by a stroke to this ground wire in the adjacent tower span. However, an inward-flowing current in this wire would still further unbalance the tower-top current summation.

For the sixth item a lightning-rod stroke of 62,000 amperes gave inward-flowing currents on all four ground wires. A continuous counterpoise wire carried 37,700 amperes inward toward the tower base.

Specimen cases in which the tower-cage current when combined with inward-flowing tower-top current was less than

Figure 2. Stroke-current curve of figure 1 reproduced. For comparison, currents from lightning-rod measurements (circles) and overhead-ground-wire measurements (triangles) are indicated

outward tower-top current are given in table IV.

The first item of this group was a direct stroke to a tower-top lightning rod with four overhead ground wires all carrying current inward to be combined with 11,870 amperes flowing up the tower. The counterpoise wires at this tower carried a combined value of 16,470 amperes into the tower base. No other strokes reached the line nearby.

The second item pertains to a stroke to the ground wire near the tower top concerned, in which two ground wires carried current inward to the tower top and two outward. Crow-foot counterpoise wires carried inward to the tower base only 3,760 amperes as compared to 9,460 upward in the tower cage.

In the third item records were obtained when a stroke occurred to the ground wire adjacent to the tower concerned. No other strokes occurred to the line in this vicinity. In the fourth record, ground-wire currents flowed outward in both directions. Adjacent strokes occurred on each side of this tower.

These specimen records show clearly the difficulties involved in simple addition of surge-crest-ammeter records. In many instances it is possible upon careful consideration of all data to recognize difficulties in the way of good checks.

Table II. Comparison of Inward and Outward Currents at Tower Top, Showing Good Agreement

Item	Combined Leg and Brace Amperes	Ground-Wire Amperes In	Ground-Wire Amperes Out	Combined Amperes Inward	Combined Amperes Outward
1	11,870	8,150	18,400	20,020	18,400
2	13,350	10,200	23,000	23,550	23,000
3	15,600	2,800	17,700	18,400	17,700
4	11,250	9,160	19,800	20,410	19,800

Some of the circumstances which militate against good checks in addition of records are included in the following summary:

1. Nearby strokes causing overlapping surges.

2. High currents in nearby structure members other than the one to which the measurement station is attached.

3. Insufficient magnetic-link records to measure crest currents when oscillations or reversed currents are present.

4. Crest-current values in the several members under consideration not being simultaneous.

The fourth of these items is concerned with the nature of the distribution of cloud and ground charge. That the complete charge participating in a stroke is spread over a considerable area is commonly accepted. Also, such oscillograms of lightning-current wave shapes as have been recorded have shown complex wave shapes. Repetitive strokes are now generally recognized and it is presumed by many that each discharge taps a somewhat different cloud charge position. Continuing from these considerations it is reasonable that the several currents in different overhead ground wire and structure members will not all reach crest at the same time, which of course is the assumption on which addition of member currents is based.

Overhead-Ground-Wire Current

In view of the difficulties involved in the problem of summation of currents in line structures it is very desirable to have field records for examination, from which a reasonable criterion of comparison of measurements from station to station can be made. Fortunately, in many cases the two stations at each end of the ground wire within the tower span are carrying the same current if no stroke occurs within the span.

Some 230 records of this type in which the sending and receiving ends were carrying the same current have been accumulated during the last three years. These records ranged from 1,000 to 28,000 amperes and are of three kinds: first, records in which two magnetic links recorded intensities within the link magnetization range; second, records in which currents were low and only the inner magnetic link recorded; and third, those cases of high currents in which the inner link was magnetically saturated and only the outer-link record was available for current interpretation. All 230 records have been summarized in table V.

In this table the average of each pair of sending and receiving end stations is accepted as a reference and the percentage of deviation of the actual recorded current from it taken. In column 2 are given the number of individual records within each per cent deviation and in column three the percentage of the total records in each deviation range.

The magnetic links are selected to record crest surge currents within an accuracy of plus or minus ten per cent. On this basis some 70 per cent of the sending and receiving end stations checked each other accurately. Several of the known circumstances working against a check and quite likely responsible for the deviations greater than plus or minus 10 per cent, are as follows:

1. In a great number of cases one station will provide two link readings from which oscillatory calibrations can be used, while the corresponding station at the adjacent tower will provide only a single link reading subject to the unidirectional calibration. If some degree of oscillation is present the two-link station will indicate a higher crest current. This circumstance accounts for the greater number of excessive differences particularly of the higher percentages.

2. Possible streamer and stroke disturbances occurring between the two stations.

3. Cases where link magnetization is disturbed prior to calibration.

Polarities of Strokes to Transmission Lines

Lightning strokes to transmission lines are predominantly negative in polarity, that is, current flows from positive earth to negative cloud. In figure 1 are summarized a total of 734 strokes accumulated from 1933 to 1936 inclusive. Of these, 685 or 93 per cent were negative and 49 or 7 per cent were positive. This total undoubtedly omits many strokes below 5,000 amperes and omits all below 2,000 amperes. That a considerable number of such low-current strokes do occur, at least under the conditions of projections of considerable height above the earth, has been definitely determined.[3] The indication is that these low-current strokes are generally of the continuing type and associated with upward-stepped leaders.

As regards cloud polarities a very interesting study has recently been reported[4] in which in addition to ground-surface gradients, soundings were made at various elevations up through the cloud by small free balloons. The results of this investigation suggest that "the main body of a thundercloud is negatively charged and that the upper part is generally charged positively." Also that "there is good evidence of the frequent occurrence of a local concentration of positive charge in the base of the cloud

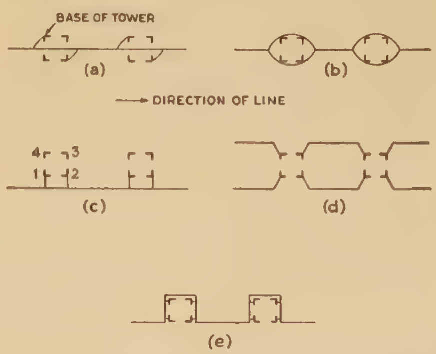


Figure 3. Typical arrangements of tower-to-tower counterpoise wires

Table III. Comparison of Inward and Outward Currents at Tower Top, Inward Greater Than Outward

Item	Combined Leg and Brace Amperes	Lightning-Rod Amperes	Ground-Wire Amperes In	Ground-Wire Amperes Out	Combined Amperes Inward	Combined Amperes Outward
1	24,820		22,100	32,500	46,900	22,100
2	21,290		21,650	32,180	42,940	32,180
3	69,630		20,350	70,000	89,980	70,000
4	58,650		23,500	70,000+	82,150	70,000+
5	42,080	57,000	40,960	None	83,040	57,000
6	58,460	62,000	26,130	None	84,590	62,000

Table IV. Comparison of Inward and Outward Currents in Tower Top, Outward Greater Than Inward

Item	Combined Leg and Brace Amperes	Lightning-Rod Amperes	Ground-Wire Amperes In	Ground-Wire Amperes Out	Combined Amperes Inward	Combined Amperes Outward
1	11,870	33,000	8,820	None	20,690	33,000
2	9,460	None	5,200	23,500	14,660	23,500
3	15,900	None	3,800	28,500	19,700	28,500
4	14,250	None	None	32,200	14,250	32,200

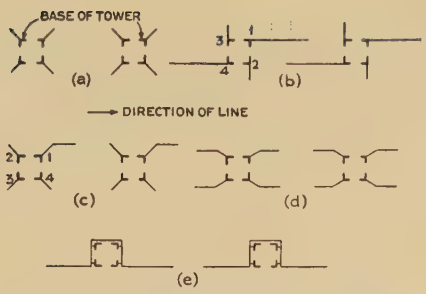


Figure 4. Typical arrangements of radial or noncontinuous counterpoise wires

usually just in front of the heavy rain center, but sometimes in other parts of the base."

Regarding the field at the ground, after combining records of some 20 storms, the authors[4] conclude that under the main body of a thundercloud the gradient is more often negative than positive. However, as the cloud approaches and recedes the ground gradient is positive and within the region of heavy rain under the main body, which rain brings down a net positive charge, the preponderance of negative gradient is markedly reduced.

From measurements[3] made by oscillograph of 55 lightning strokes to a building 1,250 feet above the street, the conclusion is reached that all strokes began with a negative cloud. Three strokes changed to positive at or near the end of the stroke and only three per cent of the total charge measured was associated with the positive portion of the strokes. In one case a continuing low current of only several hundred amperes was followed later by a negative discharge having a crest of 1,500 amperes, which was followed by a positive discharge of 2,000 amperes. These data show that mixed polarities are occasionally present in a single lightning stroke. Such a mixed polarity stroke or a sequence of mixed polarity strokes, when measured with magnetic links, will indicate an oscillatory surge and many such records have been obtained.

All magnetic-link records indicating oscillatory polarities have been interpreted through the use of an oscillatory calibration chart,[5] which was obtained in the laboratory using oscillatory calibrating surges of constant logarithmic decrement. It is obvious, therefore, that where mixed polarity surges are present and especially when the positive and negative magnitudes are of the same order, the interpretation will be correct only when the wave shape is that of a damped oscillatory capacitor discharge of constant logarithmic decrement. However, the use of such a calibration will invariably, it is believed, permit a closer approximation of the true current than would be obtained from the unidirectional polarity calibrations.

Counterpoise Wires

Counterpoise wires are in use on various systems ranging from 66 kv to 287 kv. The material used is stranded copper conductor, stranded steel conductor, stranded copperweld conductor, stranded iron wire, flat steel strip, and copper rod. The stranded copper was 1/0 and 2/0, the galvanized steel and copperweld varied from $^3/_8$ inch to $^5/_8$ inch in diameter, the copper rod was $^1/_4$ inch in diameter and the steel strip $^1/_{16}$ by 1.5 to 2 inches.

There is insufficient data to say that any of these materials or sizes is better than any other. Length of life and freedom from theft has played a large part in the choice of material.

One of the main objects of our investigation was to learn how the counterpoise functions and if possible the best arrangement of counterpoise wires. Natural lightning is very intermittent and erratic, so that an investigation of this sort is bound to progress very slowly.

Figure 3 illustrates some of the arrangements of continuous (parallel) counterpoise wires that are in use, and figure 4 shows some of the radial or discontinuous arrangements.

Distribution of Current Between Continuous Counterpoise Wires and Tower Footings

With an arrangement such as shown in figure 3*c*, readings of current in tower legs 1 and 2 (including diagonals) and in counterpoise wires were recorded in 22 cases at nine towers, and by subtraction the tower-footing current was evaluated. The summation of the readings gave distribution of current as follows:

Tower legs 1 and 2	100 per cent
Continuous counterpoise	69 per cent
Footings, legs 1 and 2	31 per cent

In five occurrences at four towers readings were obtained of current in the counterpoise wire and in all four legs of the tower, figure 3*c*, and by subtraction the footing current was obtained. The average distribution of current was approximately as follows:

Tower legs (four legs)	100 per cent
Continuous counterpoise	58 per cent
Footings (four legs)	42 per cent

With an average tower-footing resistance as measured by a Megger ground tester of 69 ohms, this would indicate an apparent counterpoise resistance of about 50 ohms.

Distribution of Current Between Radial Counterpoise Wires and Tower Footings

In an arrangement such as shown in figure 4*a*, in which each limb of the counterpoise system is 50 feet long, readings on one occasion were taken in all four tower legs and counterpoise wires, and by subtraction the footing current was found. The division of current was as follows:

Tower legs (four legs)	100 per cent
Radial counterpoise wires (four legs)	42 per cent
Footings (four legs)	58 per cent

The tower had a resistance of 47 ohms by Megger ground tester, which indicates an apparent resistance of approximately 65 ohms for the radial counterpoise system.

Table V. Ground-Wire Sending and Receiving End Comparisons

Per Cent Deviation From Average of Sending and Receiving Stations	Number of Records Within the Per Cent Deviation of Column 1	Number of Records in Per Cent Within the Per Cent Deviation in Column 1
0	41	17.7
0 to 5	80	35.0
5.1 to 10	40	17.4
10.1 to 15	23	10.0
15.1 to 20	11	4.9
20.1 to 25	8	3.5
25.1 to 30	7	3.1
30.1 to 35	4	1.7
35.1 to 40	6	2.6
40.1 to 45	4	1.7
45.1 to 50	2	0.8
50.1 to 55	1	0.4
55.1 to 60	1	0.4
60.1 to 65	1	0.4
65.1 to 70	1	0.4
Totals	230	100

In an arrangement such as shown on figure 4*c*, in which the one long wire was 250 feet long and the three short wires 50 feet long, on two occasions at the same tower readings were taken of current in the four legs and in the four counterpoise wires and the footing current was found by subtraction. The average distribution of current was as follows:

Tower legs (four legs)	100 per cent
Radial counterpoise wires (four legs)	70 per cent
Footings (four legs)	30 per cent

The tower-footing resistance by Megger ground tester was 91 ohms, giving an indicated resistance for the radial counterpoise system of 39 ohms. Of the current carried by the counterpoise wires,

the 250-foot wire with $62^1/_2$ per cent of the total length carried 68 per cent of the total counterpoise current.

In an arrangement such as shown in figure 4*c* readings were taken in the long counterpoise (250-foot) wire only and in the connecting tower leg number 1, in five cases at four towers, and by subtraction the footing current was found. The distribution was as follows:

Tower leg 1	100 per cent
250-foot radial counterpoise only	72 per cent
Footings (leg 1)	28 per cent

In 16 cases involving 12 towers readings were taken simultaneously in one long (150-foot) counterpoise wire and the corresponding tower leg 4 and in one short (40-foot) counterpoise and the corresponding leg 3 (figure 4*b*). By subtraction the footing current was found. The division of current was:

Tower legs 3 and 4	100 per cent
Radial counterpoise wires (legs 3 and 4)	78 per cent
Footings (legs 3 and 4)	22 per cent

The average footing resistance of the 12 towers was 129 ohms by Megger ground tester, and assuming legs 1 and 2 and connected counterpoise wires to have the same amount and distribution of current as legs 3 and 4, an apparent resistance of 36 ohms for the radial counterpoise system would be indicated. The calculated resistance of the radial counterpoise system from actual measurement by Megger ground tester of the individual wires when separated from the towers was approximately 50 ohms.

Distribution of Current Between Tower Footings and Combination of Continuous and Discontinuous Counterpoise Wires

A section of line is equipped with one parallel counterpoise wire, which is continuous if the distance between towers is 1,000 feet or less (figure 3*e*), and broken at 500 feet from the tower if the distance between towers is greater than 1,000 feet (figure 4*e*). In three cases involving three towers in this section readings were taken simultaneously in the tower legs, tower footings, and continuous or broken counterpoise arrangement. In all three cases the wire was continuous on one side of the tower and broken on the other. Following was the division of current:

Tower current	100 per cent
Continuous counterpoise	33 per cent
Broken counterpoise	27 per cent
Tower footings	40 per cent

The tower-footing resistance by Megger ground tester averaged 135 ohms, which would indicate an average apparent resistance of 164 ohms for the continuous counterpoise and 200 ohms for the broken counterpoise. The average actual resistance measured by Megger ground tester of the continuous counterpoise wires when disconnected from the towers was 65 ohms and of the broken counterpoise wires 74 ohms.

Experimental Combinations of Continuous and Radial Counterpoise Wires and Driven Rods

An experimental installation of continuous (parallel) counterpoise wires, combined with two radial counterpoise wires extending at right angles, one in each direction (figure 5*a*), was made in a sandy high-resistance territory. The continuous counterpoise wire was connected to one corner of a three-legged tower and the radial wires to the other two legs. The length between towers was about 500 feet, so that it might be considered that 250 feet of continuous counterpoise was associated with each tower in each of two directions. Each right-angle radial counterpoise was 250 feet long, or 500 feet total per tower.

In 1937 there was a stroke to the overhead ground wire between two towers. By means of magnetic links on the counterpoise wires and the tower legs, the current was evaluated and the pickup was found to be approximately as follows (the tower footing pickup being found by subtraction):

Total current	100 per cent
Continuous counterpoise pickup	38 per cent
Right-angle counterpoise pickup	43 per cent
Footing pickup	19 per cent

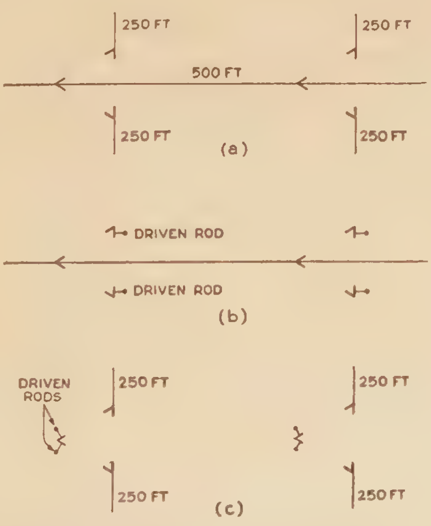


Figure 5. Experimental installations of tower-to-tower right-angle counterpoise wires and driven rods

Another experimental installation consisted of a continuous counterpoise connected to one corner of a three-cornered tower, supplemented by one or two deep-driven rods connected to the other corners, figure 5*b*, and still a third installation consisted of right-angle counterpoise wires 250 feet long extending from two corners of the tower and one or two deep-driven rods from the third corner, figure 5*c*.

In 1938 a stroke occurred to the overhead ground wire between two towers, to the left of which was the arrangement of counterpoises shown in figure 5*b* and to the right the arrangement shown in figure 5 *c*. Current was measured in the counterpoise, tower legs, and driven rods and found by subtraction in the tower footings. The distribution of current between the sections arranged as in figure 5*b* and figure 5*c* was as follows:

Total stroke current	100 per cent
Pickup in section 5*b*	74 per cent
Pickup in section 5*c*	22 per cent
Pickup in footings in both sections	4 per cent

Four towers were involved in the section arranged as in figure 5*b*. The footing resistance of these towers varied from 540 to 1,400 ohms, with an average of 831 ohms. The combined resistance of the footings and the driven rods varied from 9 to 23 ohms, with an average of 13 ohms. The apparent counterpoise resistance calculated from the distribution of current was about 61 ohms. The distribution of current between the counterpoise, driven rods, and footings was approximately as follows:

Total current picked up in section 5*b*	100 per cent
Picked up by driven rods	81 per cent
Picked up by continuous counterpoise	18 per cent
Picked up by footings	1 per cent

Three towers were involved in the section arranged as in figure 5*c*. The footing resistance of these towers varied from 665 to 910 ohms, with an average of 808 ohms. The combined resistance of the footings and the driven rods was about 13 ohms for all towers. The apparent right-angle-counterpoise resistance calculated from the distribution of current was about 46 ohms. The distribution of current between the right-angle counterpoise, driven rods, and footings was approximately as follows:

Total current picked up in section 5*c*	100 per cent
Picked up by driven rods	77 per cent
Picked up by right-angle counterpoise	22 per cent
Picked up by footings	1 per cent

It is probable that the driven rods penetrated through the sand to underlying clay or loam, while the counterpoise wires were buried in sand at very high resistance. The counterpoise wires in this experiment were equally effective whether continuous and parallel to the line or at right angles to the line. It is also apparent that in this particular territory, the deep-driven rods are more effective than the counterpoise wire.

Conclusions

1. The frequency of occurrence of lightning strokes of various current amplitudes is about the same whether measurements are obtained directly in lightning rods and overhead ground wires or amplitude values are obtained by addition of tower member and adjacent tower currents.

2. The average lightning stroke current is about 30,000 amperes. The upper level of strokes is about 150,000 amperes and possibly less than one per cent of all strokes reach this value. Stroke currents as measured range down to 2,000 amperes. Other observers using oscillographic means report strokes as low as several hundred amperes crest.[3] Some 93 per cent of all lightning strokes reaching transmission lines are of negative polarity, that is, the cloud is negative and the ground positive.

3. A summation of currents at the tower top, considered as a center for tower, overhead-ground-wire, and lightning-rod currents, shows inward and outward flowing currents equal in 25 per cent of all cases. In 50 per cent of the cases inward flowing currents are larger than outward, and in the remaining 25 per cent outward currents are larger than inward currents.

4. Seventy per cent of all records of currents flowing in overhead ground wires at adjacent stations at the ends of the same span show the sending and receiving ends to agree within plus or minus ten per cent.

5. All arrangements of counterpoise wires that have been tried have given improvement in the flashover performance of the lines, some arrangements more than others. The counterpoise wire reduces the resistance at the tower footing, reduces the earth potentials, and holds down the tower potential, thereby preventing insulator flashover.[2]

6. The data show that counterpoises of various arrangements pick up from 40 to 80 per cent of the current, as compared with the tower footings which pick up from 60 to 20 per cent. This relative amount of pickup depends on the length and arrangement of the counterpoise wires, the tower-footing resistance, and possibly other factors.

7. Counterpoise resistance calculated from the division of current between counterpoise and tower footing, agrees with the resistance measured by Megger ground tester and current divides substantially in accordance with the resistance. An exception is that of the continuous and long discontinuous or broken counterpoises, which have a low measured resistance but an actual apparent resistance to lightning current much higher and of the same order as the usual radial counterpoise. This indicates that the entire length of the continuous counterpoise is not effective in reducing the resistance at the foot of the tower.

8. In territory in which a considerable depth of sand lies on the surface, producing a very high resistance condition, driven rods offer a very effective means of reducing the tower resistance. Tests in which driven rods were compared with the continuous and right-angle counterpoises of about equal effective length, showed about 80 per cent of the current picked up by the driven rods and 20 per cent by the counterpoise wires lying in the high-resistance sand.

9. Magnetic links have proved to be very valuable in obtaining the data on current necessary for the analysis of the counterpoise problem.

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Discussion

F. W. Hartzell (The Commonwealth and Southern Corporation, Jackson, Mich.): This paper presents in a valuable form additional information that might be used in attacking the ever-present problem of improving the performance of high-voltage transmission lines during the lightning seasons.

In reviewing previous literature on the subject of counterpoises, of which this paper deals quite extensively, it is found that only a limited amount of actual field data is available, some of it being of conflicting nature. This study, however, gives an interesting picture of the distribution of surge currents throughout the grounding systems of transmission line towers as determined by actual measurements.

It might be pointed out that the use of driven ground rods is sometimes limited by the depth of soil to rock, although driven rods frequently penetrate to depths of 100 to 150 feet. These deep ground rods compare in length to some of the counterpoises that have been under investigation, so some interesting light might be thrown on the subject if these ground rods were treated as vertical counterpoises as compared to the parallel and radial counterpoises described in this paper.

It also becomes evident that individual towers, or groups of towers, should be considered separately according to ground characteristics when prescribing lightning-resistant features to any transmission line. A careful survey of the conditions to be encountered along a transmission line is therefore imperative before recommendations are made for lightning protection.

K. B. McEachron (General Electric Company, Pittsfield, Mass.): It is not enough to discover the maximum current in lightning strokes, it is also necessary to determine how often currents of any given magnitude may occur, and Lewis and Foust have established curves, as given in figure 1 of the paper, which for several years back have been used in determining the probability of strokes of any given magnitude. These data have been of much value in helping to determine just how far one is justified in proceeding in an effort to protect against direct strokes. These data could be of still more value if the authors could give some data with reference to the number of strokes per mile of line per year which they have experienced. Information is needed with respect to stroke severity in different localities, but this is also a statistical problem which requires much time to secure a satisfactory answer.

In connection with the discussion of polarities of strokes, I would like to point out that, in reference 3 of the paper, I presented data showing that the continuing type of stroke occurred not only to the Empire State Building but was found in many strokes to substantially flat terrain. However, the evidence, thus far available, indicates that upward-stepped leaders occur from structures several hundred feet in height, and occur in a smaller percentage of the strokes as the structure height becomes lower. Thus far, I have no evidence that upward leader strokes occur to transmission lines of the usual height. Continuing strokes with downward initial leaders are common, and undoubtedly occur to transmission and distribution circuits. The continuing stroke is like a d-c arc between cloud and ground with superimposed current peaks. The arc current is often quite small, but may have a magnitude of several hundred amperes with a duration of a fractional part of a second.

It is of importance to recall that direct strokes from negative clouds release a positive bound charge on conductors in the cloud field, which may be of importance on low-voltage circuits when the rate of field change is sufficiently rapid. Only the current peaks will have such an effect, so that in an oscillogram of induced current in such a conductor the continuing part would be absent.

Although the magnetic links frequently show reversal of polarity of current in the inducing conductor, yet there is no evidence that lightning oscillates. It may change polarity, and the available data indicate that it does reverse. However, there is no apparent relation between the magnitude of the initial current and the subsequent reversal. This seems quite reasonable, if the cloud is considered as made up of groups of

Table I. Lightning-Current Measurements, 1938 Data

Area Is for Section in Which Magnetic Links Are Installed

Item No.	Test No.	Tower No.	Main Members			Lesser Members			Totals			Ratios—Total to Main		
			I_m	A_m	D_m	I_l	A_l	D_l	I_t	A_t	D_t	R_i	R_a	R_d
1	1	503	10,400	20.24	514	8,900	6.90	1,290	19,300	27.14	713	1.85	1.34	1.39
2	1	538	37,000	12.16	3,062	49,100	9.30	5,280	86,100	21.46	4,000	2.33	1.76	1.30
3	1	539	40,100	16.72	2,400	66,900	8.94	7,480	107,000	25.66	4,175	2.67	1.53	1.74
*4	1	550	10,000	23.00	436	2,000	7.12	281	12,000	30.12	398	1.20	1.31	0.91
5	1	626	27,500	23.00	1,195	14,500	7.12	2,040	42,000	30.12	1,395	1.53	1.31	1.16
*6	2	540	6,800	16.72	407	0	9.30	0	6,800	26.02	261	1.00	1.56	0.64
7	2	551	15,500	36.44	425	17,800	8.42	2,120	33,300	44.86	955	2.15	1.23	2.25
8	2	625	54,200	16.72	3,240	88,500	9.30	9,500	142,700	26.02	5,490	2.64	1.56	1.69
*9	2	626	9,000	23.00	391	0	7.12	0	9,000	30.12	298	1.00	1.31	0.76
10	3	503	9,600	20.24	474	7,800	6.90	1,130	17,400	27.14	642	1.82	1.34	1.35
*11	3	504	7,700	12.16	633	3,800	6.90	550	11,500	19.06	604	1.50	1.57	0.95
12	3	541	30,000	25.30	1,185	20,100	12.34	1,630	50,100	37.64	1,330	1.67	1.49	1.12
13	3	542	23,900	12.16	1,965	18,000	9.30	1,935	41,900	21.46	1,953	1.75	1.76	1.00
14	3	543	32,300	23.00	1,400	27,300	7.12	3,830	59,600	30.12	1,980	1.85	1.31	1.41
15	3	544	27,300	16.72	1,633	23,100	9.30	2,480	50,400	26.02	1,935	1.85	1.56	1.18
16	3	549	26,400	16.72	1,472	18,900	9.30	2,030	45,300	26.02	1,740	1.72	1.56	1.18
17	3	552	37,100	16.72	2,220	31,800	9.30	3,410	68,900	26.02	2,650	1.85	1.56	1.19
18	3	622	21,600	23.00	940	13,400	7.12	1,885	35,000	30.12	1,163	1.62	1.31	1.24
*19	3	623	3,200	16.72	185	0	9.30	0	3,200	26.02	123	1.00	1.56	0.66
*20	3	624	7,700	16.72	451	1,200	9.30	129	8,900	26.02	342	1.15	1.56	0.76
*21	3	627	4,600	12.16	379	0	8.94	0	4,600	21.10	218	1.00	1.73	0.57
22	4	540	12,200	16.72	732	10,000	9.30	1,075	22,200	26.02	855	1.82	1.56	1.17
23	4	549	29,200	16.72	1,745	16,900	9.30	1,815	46,100	26.02	1,770	1.58	1.56	1.02
24	4	550	30,400	23.00	1,320	18,700	7.12	2,630	49,100	30.12	1,630	1.62	1.31	1.23

* Due to low value of lightning current it is probable that more current than is recorded was present in lesser members. Such being the case, the true ratios would be nearer other ratios recorded.

I_m, I_l—Total current in amperes in main and lesser members, respectively
D_m, D_l—Current density in amperes in main and lesser members, respectively
I_t—Total current in amperes—all members
A_t—Total cross section in square inches—all members
D_t—Current density in amperes—all members
R_i—Ratio: total current to current in main members
R_a—Ratio: total cross section to cross section in main members
R_d—Ratio: total current density to current density in main members
A_m, A_l—Total cross section in square inches in main and lesser members, respectively

charged insulated water drops which may group themselves in unpredictable configurations, both as to size of the group and location. In the laboratory, the discharge across 30 feet of air may oscillate if the series resistance is low enough, but in nature the cloud is not a conductor, and the availability of charge at any given point of discharge is not great, and thus time factors are introduced which are not normally present in the laboratory generator. Since calibration of the magnetic-link installation had to be made in some systematic manner, the use of the laboratory oscillatory wave was the best compromise.

It is indeed fortunate that the measurement of stroke current in the lightning rod at the top of the tower so often checked the summation of currents in the tower legs, since these data have been so widely used. In view of conclusion 2 of the paper, do the authors now feel it desirable to revise slightly downward the curve of figure 1?

R. M. Schahfer (nonmember) and **W. H. Knutz** (both of Northern Indiana Public Service Company, Hammond): The recent report of Messrs. Lewis and Foust provides additional data needed in studying and applying protective measures against lightning. However, by neglecting the current carried by the lesser tower members or by assuming any fixed ratio of this current to the current carried by the main tower members, it is entirely possible that the conclusion as to the total structure current may be in error.

With the foregoing thought in mind, we installed magnetic links on 29 132,000-volt double-circuit steel towers. These installations were made just before the 1938 lightning season. The magnetic links are installed about 15 feet above the ground on all tower members which provide a lightning current path to ground. From 14 to 18 brackets and 28 to 36 magnetic links are used per tower.

During the 1938 lightning season 24 towers provided lightning-current readings. Current values, steel-member areas, current densities, together with pertinent ratios are shown in table I of this discussion.

Summaries of current and current-density ratios taken from the table are:

	Total Current to Current in Main Members	Total Current Density to Current Density in Main Members
Average	1.67	1.16
Maximum	2.67	2.25
Minimum	1.00	0.57

Eliminating the probable low values designated by an asterisk(*) these ratios are:

	Total Current to Current in Main Members	Total Current Density toCurrent Density in Main Members
Average	1.90	1.33
Maximum	2.67	2.25
Minimum	1.53	1.00

From the above figures, the conclusion would be drawn that the ratio of total tower current to current in the main members has a variable ratio which is greater than heretofore suspected, and that the total structure current may therefore be in excess of values previously obtained by applying a general factor to the current of the main members.

Our total tower current values will, if plotted as a cumulative graph, form a curve somewhat above curves shown by Messrs. Lewis and Foust in figure 1.

The lightning investigation work from which these data were obtained is being continued in 1939.

W. W. Lewis and **C. M. Foust:** Doctor McEachron suggests that the authors give some data with reference to the number of strokes per mile of line per year. The authors have such data on the same lines covered by the curves of figure 1, and for the same years. The figures vary widely on account of actual differences in the number of storms and strokes and perhaps partly for the reason that some lines are well covered with magnets throughout their length, thus giving a fair average per mile, while other lines have magnets only for short lengths, probably selected for the known exposure to lightning. Naturally, the strokes per mile are high at these latter classes of installation. For one line, completely equipped with magnetic links, the strokes per mile varied from 0.22 to 0.87 for different years. On another line, only six per cent of its length equipped with links, the strokes per mile varied from 15.4 to 39.2. The data for the other lines fell in between these extremes.

Doctor McEachron asks in view of con-

Arc-Furnace Loads on Long Transmission Lines

T. G. LeCLAIR
MEMBER AIEE

LARGE electric arc furnaces are loads which frequently introduce special technical problems when served from a central-station system. The fluctuations in the load taken by the furnaces are violent, and this characteristic combined with the inherently low power factor of this type of load results in a serious flicker problem. The low power factor also may require power-factor correction, in order to maintain a reasonable voltage level and reduce transmission losses. A further complication is that the arc is an excellent source of higher-harmonic currents and voltages. Where the load or the supply lines are close to telephone circuits, this may necessitate special measures to prevent telephone interference.

Long transmission lines accentuate the problem mentioned. The longer the line, the greater will be the extent of the voltage flicker suffered by other customers on the same transmission system. On a system which operates near its stability limit, the fluctuations in line load caused by the furnaces may result in a lower allowable loading of the system. In extreme cases, load fluctuations may be timed in such a manner as to cause instability, even though the initial loading is well below the normal stability limit of the system.

Large furnace loads on transmission lines are not common. However, this type of load is increasing in importance and means should be found to handle these loads at a reasonable cost. This paper describes the solution of one particularly difficult problem, the details of which should be of value to other companies when considering the supply to proposed intermittent loads.

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Nature of Load

The Northwestern Steel and Wire Company at Sterling, Ill., has a wire mill and small steel mill, which are equipped with the usual complement of lighting and power load. Within the past few years, two three-phase electric arc furnaces with a nominal rating of 7,500 kva each have been installed as a source of steel supply. These furnaces melt a wide variety of scrap iron and steel. The furnaces are first charged with cold metal, and when this initial charge is melted, additional cold scrap is added before the metal is poured. Both the initial charge and the back-charging result in violent load changes. Figure 1 shows a photograph of one of these furnaces in use.

Supply System

The load at Sterling is supplied through a bank of 20,000-kva transformers, 132/13.8-kv, which are connected to a 132-kv line from Dixon, Ill. As shown on the diagram, figure 2, the location of Dixon is almost at the center of a 220-mile single-circuit transmission system, connecting the Powerton and Waukegan generating stations. There are two other independent 132-kv transmission circuits from Powerton to Chicago, each of which operates on a single generating unit at Powerton.

Connected to the distribution system fed from Dixon are several hydroelectric generators. However, the average running capacity of all these generators is less than 4,000 kw. There is also a steam generating station at Dixon, but this station is normally operated only for a short time during the peak period of the year. Therefore, practically the entire load distributed from Dixon is dependent upon the 132-kv transmission system for its supply. The Dixon distribution system serves most of the territory of the Illinois Northern Utilities Company, in an area of several thousand square miles.

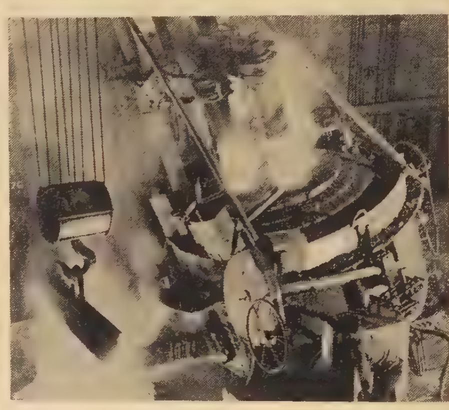


Figure 1. Pouring metal from a 7,500-kva electric arc furnace

Load Characteristics

The Northwestern Steel and Wire Company load has a half-hour integrated maximum demand of about 17,000 kw at about 85 per cent power factor. The indicated demands occasionally exceed 25,000 kw, or 30,000 kva, most of this demand being the load of the two electric furnaces. The demand of the general power load is about 3,000 kw, not including the wire mill. The lighting load of 75 kw, served at 13,800 volts, was connected to the city distribution system which is supplied from the Dixon 33-kv bus. This was because the voltage fluctuations caused by the electric furnaces were too great for the operation of mercury-vapor lamps.

clusion 2 of the paper if the authors feel it desirable to revise slightly downward the curve of figure 1 for stroke currents. The curve of figure 1 is the result of 734 strokes and was obtained by adding current in all towers affected by a stroke. Some question has been raised as to the validity of this method. The circles and triangles of figure 2 are based on only 80 strokes, but the data were obtained in each case close to the stroke. In the case of the lightning rods, the data involved only one reading for each stroke and in the case of the ground wires involved the addition of two readings. For this reason the authors proposed a compromise upper limit of 150,000 amperes, subject to revision on the accumulation of further data.

Messrs. Schahfer and Knutz present some valuable data as to the distribution of current in the main and lesser members of the tower structure. The average ratio of total current to current in main members of approximately 1.7 to 1.9 agrees with ratios found on other systems. As indicated in the paper this ratio depends to some extent on the symmetry of the counterpoise arrangement with respect to the tower legs, as well as on the actual ratios of cross sections of lesser and main members.

The sudden changes in arc resistance and the frequent short-circuits between electrodes during the process of melting down scrap, result in a violently fluctuating characteristic for the furnace load. The extent of these load fluctuations can best be illustrated by reference to figure 3, a chart from the graphic wattmeter connected to the steel and wire company total load. The section of the chart is a typical example of the period from the initial charging to the pouring of the arc furnaces. As indicated on the chart, the load may frequently go from zero to over 20,000 kw within a period of one to five minutes, or drop off at the same rate. In spite of the violent fluctuations, the average load throughout a 24-hour period is about 60 per cent of the half-hour integrated maximum demand.

Even a close inspection of graphic meter charts does not tell a complete story on the nature of load fluctuations. The load, which apparently swings quickly from zero to 20,000 kw, does not actually make this change in one step, but rather increases by a series of steps. The maximum instantaneous step was determined by oscillograms and found to be about 10,000 kva. These instantaneous changes take place within a period of a hundredth to a tenth of a second. Figure 5 shows one such load swing with a maximum change of 7,000-kva in one cycle. These random fluctuations may come as frequently as six to ten times per second, and are very disturbing to lighting service.

Methods of Voltage Control

Voltage control was first attempted by means of automatic tap changers on the 20,000-kva transformer bank supplying the 13.8-kv bus. The adoption of this scheme was based on an estimated maximum load of 10,000 kw and on incomplete information about the arc-furnace characteristics. The tap changer was partially successful in following the slower load fluctuations of the type indicated on the wattmeter chart. In this service the tap-changer mechanism was subjected to as many as 900 operations per day.

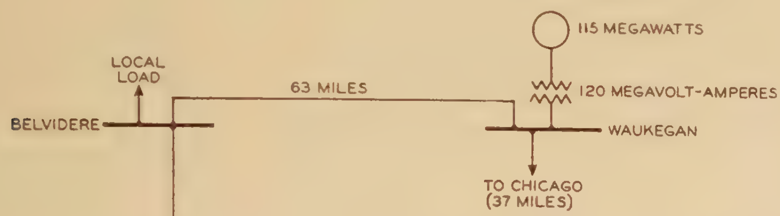
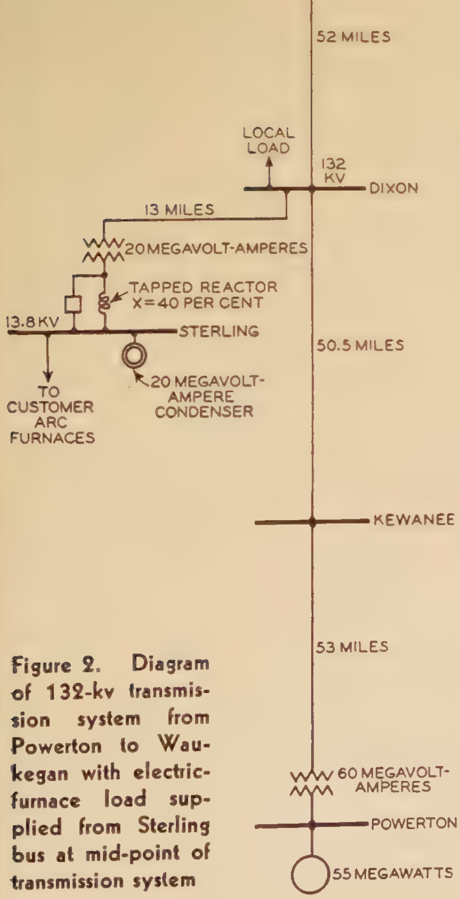



Figure 2. Diagram of 132-kv transmission system from Powerton to Waukegan with electric-furnace load supplied from Sterling bus at mid-point of transmission system

This number of operations was reduced by equipping the voltage regulator with a time delay. The tap changer, of course, had practically no effect on the Dixon 132-kv bus, as indicated in the sample chart (figure 4). This voltage chart does not reflect the real extent of the flicker, because it is from an instrument with a very slow response, and shows no record of the more rapid instantaneous voltage changes.

As previously stated, the tap changer was reasonably satisfactory for maintaining the average voltage constant on the customer's bus. However, it could not follow voltage changes of the type illustrated in figure 5. The tap changer was also of no value in controlling the voltage on the Dixon bus, which supplies the general distribution system. Several methods were considered for controlling the more rapid voltage fluctuations and for stabilizing the voltage on the 132-kv system.

One method of voltage control considered was the use of a motor generator set. This solution is quite commonly used for smaller intermittent loads. For a load with a very short time characteristic, such as a welding machine, a motor generator equipped with a flywheel and using an induction motor is very satisfactory, as the flywheel can smooth out the sudden demands. For a furnace with a load factor of 50 per cent or more, the flywheel, of course, is of no benefit. To supply the load under consideration, a motor generator set would need to be at least 20,000 kva in capacity, which would be quite expensive. In addition to its high cost, the voltage regulation on the bus supplying the furnace would be very unsatisfactory. It would certainly be less satisfactory than that obtained with the transformer connected to the high-voltage system.

A series booster, connected as shown in figure 6, was considered as an inexpensive

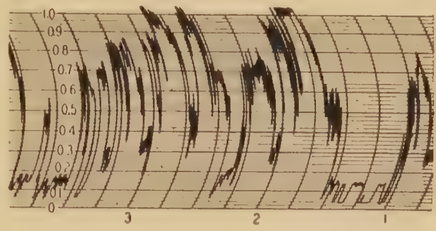


Figure 3. Arc-furnace load curve

Typical kilowatt load cycle of Northwestern Steel and Wire Company load from charging of furnaces to pouring. Full scale = 20,000 kw

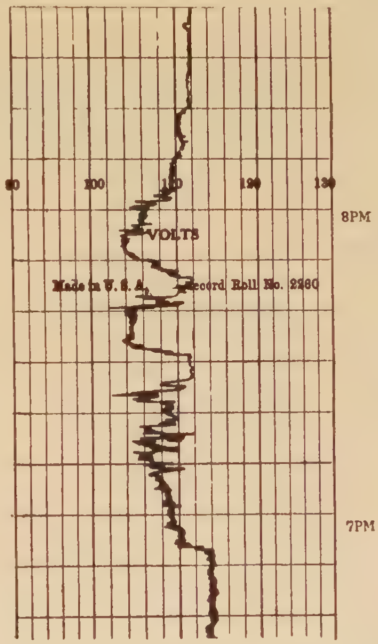


Figure 4. Effect of furnace load on Dixon 132-kv bus voltage—condition before installation of condenser at Sterling

Meter does not respond to momentary voltage changes. Multiplier: 1,200

solution. This series booster would have its exciting winding in series with the supply to the furnace load; its booster winding would be between the 13.8-kv bus and the supply to the mill and lighting load. This would improve the voltage for the general service, but would

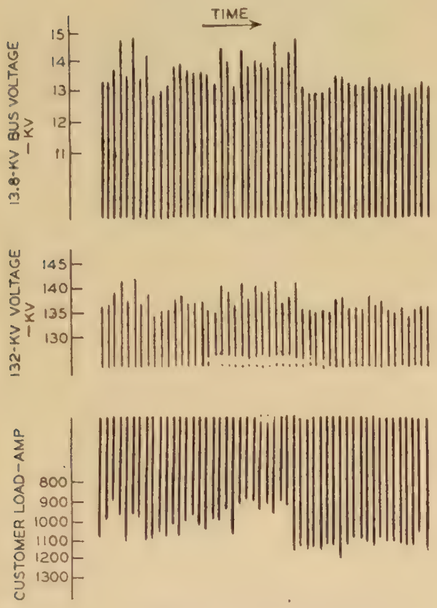


Figure 5. Oscillograms of typical changes in arc-furnace load and effect on bus voltage—no reactor, no condenser

C-phase records taken at Sterling (see figure 2)

Top—13.8-kv bus voltage
Center—132-kv voltage
Bottom—customer load current

To obtain an accurate measurement of the variations in voltage with variations in load a very large deflection was used on the voltage elements of the oscillograph. However, with this large deflection the waves from the various elements would interfere on the record and a special technique was used so that only the top of each oscillograph wave was recorded, the balance being blocked off. This accounts for the unusual appearance of the oscillograms. Space did not permit a more detailed explanation of the technique for obtaining partial oscillograph waves

make the furnace regulation poorer and would not improve the voltage for the other Illinois Northern Utilities Company customers.

Another scheme considered was that of series capacitors. These could be connected in the supply transformer secondary leads or in the 132-kv line, or divided in two parts and connected in both places. A series capacitor will neutralize a part of the reactive load due to the line and transformer reactance. The capacitor could be made large enough to maintain practically constant voltage on the furnace bus, but it would not improve regulation on the Dixon 132-kv bus. Since the electric furnaces are subject to frequent short-circuits the series capacitors would require suitable protection against damage from this source. There was also a possibility of telphone interference, as series capacitors will tend to accentuate rather than reduce the effect of harmonic current.

Condenser Installation

The solution which promised to solve the regulation problem for this customer and the general system and the one finally adopted was the installation of a 20,000-kva synchronous condenser connected to the 13,800-volt bus at Sterling which supplies the furnace load. This con-

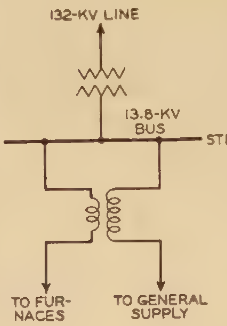


Figure 6. Series booster

Proposed connection of series booster to maintain constant voltage on general supply

denser was designed with somewhat special characteristics to obtain the maximum benefit for this application.

The synchronous condenser is useful for such an installation as this in three different respects. First, the synchronous-condenser output improves the system power factor, which in turn is of benefit in improving voltage regulation and reducing transmission losses. Second, with gradual variations in load the synchronous condenser can maintain constant voltage on the customer's bus by the action of an automatic voltage regulator. Third, with instantaneous changes in load the inherent characteristics of the synchronous condenser tend to limit the voltage change and thereby reduce lamp flicker, before the voltage regulator has had time to take effect. This is accomplished because of the instantaneous change in output of the condenser which takes place with a sudden change in terminal voltage. Fortunately, the action of the condenser in maintaining constant system voltage also tends to maintain a satisfactory system power factor.

Since the voltage dips on the 132-kv system are proportional to the reactive kilovolt-amperes supplied from this system to the furnace load, it was possible to decrease the flicker on this system by transferring the greater part of the sudden changes in reactive load to the synchronous condenser. This was accomplished by the insertion of a special buffer reactor between the 13.8-kv secondary winding of the 132-kv transformer bank and the bus to which the synchronous condenser and the furnace load are connected. This reactor was equipped with taps so that the amount of reactance could be varied after installation in order to use the value which would transfer the maximum reactive kilovolt-ampere load fluctuation to the synchronous condenser without causing trouble from surging of the condenser. A short-circuiting breaker was installed to take the reactor out of service at any time that the condenser or furnaces are not operating.

Table I shows a comparison of the calculated benefits obtained by the vari-

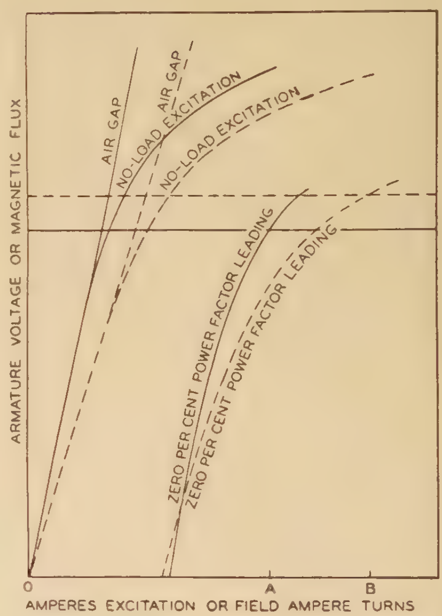


Figure 7. Synchronous-condenser saturation curves

Comparative saturation curves of synchronous condenser with normal design and special design for this application. Solid lines show normal characteristic and dashed lines show characteristic with increased air gap and higher flux density in armature

ous corrective means described. This tabulation indicates not only the extent of the voltage dips with a given change in load, but also the resultant reactive load which the system must supply with the corrective device in service.

The actual flicker without any correction was greater than that calculated.

Table I. Methods of Correcting Voltage Flicker

Calculated Effect of Various Means Proposed to Reduce the Voltage Flicker Caused by Instantaneous Load Changes on Electric Arc Furnaces. Balanced Three-Phase Load Assumed Although Most Instantaneous Swings Are Unbalanced

Corrective Equipment	Voltage Fluctuation in Per Cent for Instantaneous Swing of 10,000 Kva at 75 Per Cent Power Factor: Sterling 13.8 Kv	Sterling 132 Kv	132-Kv Reactive Load on System for Steady Customer Load of 20,000 Kw at 80 Per Cent Power Factor (Kilovolt-Amperes)
No corrective means	8.2	3.6	19,300
10,000-kva condenser, no reactor	5.3	2.5	7,900
20,000-kva condenser, no reactor	4.2	2.0	2,100 leading
10,000-kva condenser, 40 per cent reactor (20,000 base)	10.1	1.8	16,300
20,000-kva condenser, 40 per cent reactor	6.7	1.2	6,300
20,000-kva condenser, 20 per cent reactor	5.8	1.5	2,100
20,000-kva motor generator set	9.9		
10 per cent series capacitor (20,000 base)	4.6	3.5	15,400
Booster transformer	0* 9.0**	3.7	20,000

* General power supply. ** Supply to arc furnaces.

These differences are due primarily to the fact that the increment loads involved in the sudden changes in load are at very low power factors. Also, the sudden changes are usually single-phase changes, while the calculations are based on a three-phase load. By observation of lamp flicker, which is the final measure, the improvement due to the condenser is appreciably better than expected from calculations.

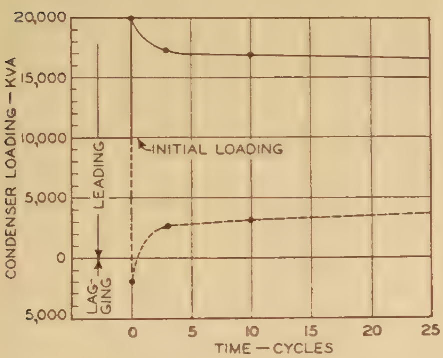


Figure 8. Condenser performance curve

Calculated performance of 20,000-kva synchronous condenser, excited for 10,000 kva at normal voltage. The solid line shows the change in output when the terminal voltage is suddenly dropped ten per cent. The dashed line shows the change when the terminal voltage is suddenly increased ten per cent. Both curves are based on constant exciter voltage

Condenser Design

The synchronous condenser was designed especially to meet the demands of this rapidly fluctuating load. It is necessary for the condenser to produce a large change in reactive kilovolt-amperes for a given variation in voltage. This may be accomplished by designing the machine so that the effective saturated values of subtransient and transient reactances are low. For an application of this kind, the amount of saturation that is effective is not the usual "rated voltage" value of reactance (that is, the reactance effective on short circuit from rated voltage and no load) but is a considerably lower value because the internal voltage is appreciably above normal and consequently the saturation is greater than at normal voltage. The manufacturer's tests and calculations for this machine indicate that the "rated voltage" saturation factor for transient reactance is about 0.91, while the saturation factor effective at full load during small voltage changes is about 0.67. The low reactances and saturation factors in this case were produced by working the machine at fairly high magnetic densities, increasing the saturation of the various parts, and increasing the air gap.

Figure 7 shows characteristic curves for a condenser of normal design compared with one having these special features. In this figure, the solid lines show the no-load and full-load saturation curves for a normal condenser design and the dashed lines are the characteristics for this condenser. It should be noted that the increased gap requires greater excitation for a given terminal voltage or armature flux density. Furthermore, the machine works at an increased armature flux density and this results in further increased excitation for the full-load point. *OA* represents the field excitation for full load and normal voltage on a standard machine and *OB* is the excitation on this machine for the same condition. Obviously, this increased field will result in better voltage regulation.

The result of these changes was a machine with an unsaturated subtransient reactance of 22 per cent, an unsaturated transient reactance of 30 per cent,

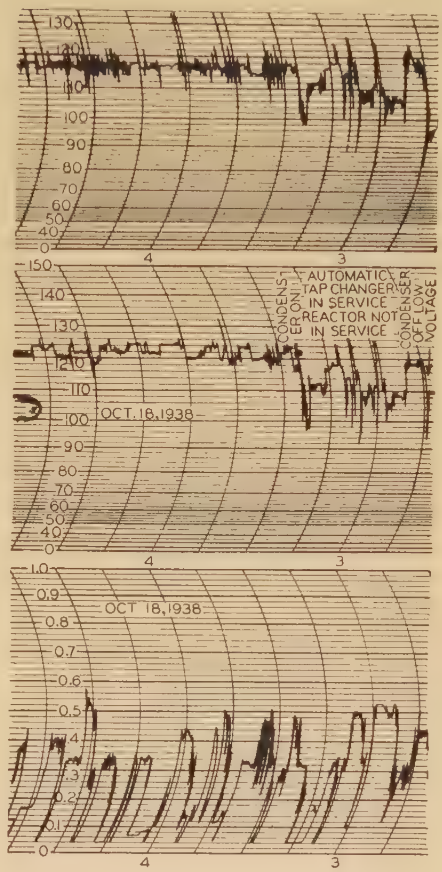


Figure 9. Effect of synchronous condenser on voltage regulation

Sections of three simultaneous graphic charts at Sterling to show benefit of condenser. No condenser and no reactor from 2:45 to 3:25 p.m. Condenser in service with 20 per cent reactor after 3:25 p.m.

Top—13.8-kv bus voltage × 120
Center—Transformer secondary voltage × 120
Bottom—Customer kilowatt demand × 39,000

and a synchronous reactance of 124 per cent. These subtransient and transient values were checked by an oscillograph test after installation.

Figure 8 was drawn to illustrate the calculated performance of this synchronous condenser for a sudden change in terminal voltage due to a sudden change in the customer's reactive load. This curve shows the variation in condenser loading with respect to time, on the assumption that a ten per cent change in terminal voltage is applied while the condenser is excited for 10,000 reactive kva loading at normal voltage. The instantaneous

change in output for a ten per cent change in voltage is at least 10,000 kva.

Results Obtained

The improvement in regulation is well illustrated in the charts of figure 9. These charts are a short section taken under a typical load condition. The charts illustrate a brief period during which the condenser was out of service and the reactor short-circuited; followed immediately by a period with the condenser and reactor in service. The comparison is therefore under directly similar load conditions. The beginning of each chart is representative of conditions before the installation of the condenser, and the remainder representative of the present conditions. The graphic charts, of course, are not capable of showing either load or voltage changes which take place in a small fraction of a second. Such sudden changes are shown in the oscillogram of figure 10, which was also taken with the condenser in operation, and with a 20 per cent reactance between the condenser bus and the 13.8-kv secondary of the main transformer bank. The complete oscillograms contain records of 12 elements, showing the currents and voltages on all phases. The records from the other elements were less satisfactory and were not reproduced because they do not add to the clarity of the picture. The bottom record on the oscillogram is good for comparative purposes only. It was obtained from a single-phase watt element in the oscillograph. This element records the product of current in one phase, and a voltage which is 30 degrees out of phase with this current. Its record serves to show the nature of the power swings of the condenser.

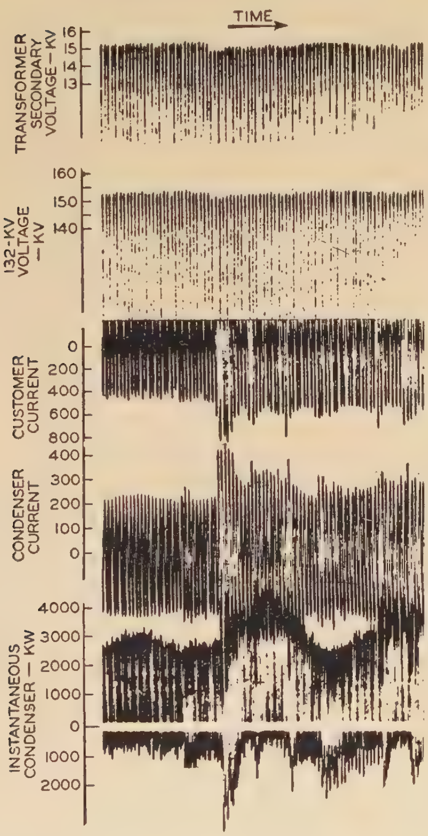


Figure 10. Oscillogram of condenser operation with 20 per cent reactor—effect of sudden change in load current on bus voltage and condenser loading

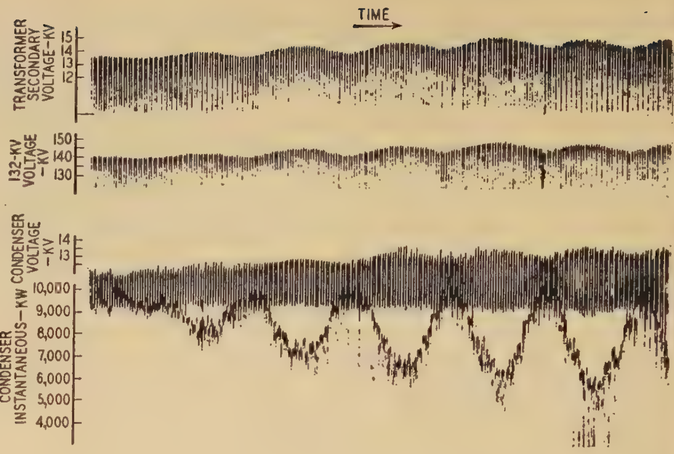
Reading from top to bottom, records are from elements at following points at Sterling (see figure 2)

1—Transformer secondary voltage
2—132-kv system voltage
3—Amperes in supply to customer
4—Amperes in synchronous-condenser leads
5—Instantaneous watts; product of condenser phase current and voltage between phases

An attempt was made to get the maximum benefit of the condenser in smoothing out the system voltage by using a 40 per cent reactance between the transformer and the condenser bus. This increased reactance was effective in further reducing the voltage flicker caused by the load changes, but resulted in hunting of the condenser with respect to the remainder of the system. A series of rapid load changes may be timed in such a manner as to have a cumulative effect if the reactance between the condenser and the system is too high. In a few instances, with the 40 per cent reactor, this cumulative effect was sufficient to cause the condenser to pull out of step and trip off the system.

The oscillogram of figure 11 illustrates a typical case of condenser hunting. This shows the steadily increasing swing in the loading of the condenser. The single-phase watt element of the oscillograph is again connected in such a way as to measure the product of the amperes in one phase of the condenser and a voltage 30 degrees out of phase with this current. Only the top half of this record is reproduced, because the bottom half on the original film was not clear enough for printed reproduction. It is interesting to note that hunting results in greater voltage fluctuations on the primary and secondary sides of the transformer bank than those which took place on the condenser bus, which supplies the customer load. This can be explained by a study of the distribution of reactance on the system diagram.

Figure 11. Oscillogram of condenser operation with 40 per cent reactor—voltage oscillations on high-voltage system caused by condenser swinging



Reading from top to bottom, records are from oscillograph elements at following points at Sterling (see figure 2):

1—Transformer secondary voltage
2—132-kv system voltage
3—Sterling bus voltage
4—Instantaneous watts; product of condenser phase current and voltage between phases

Wave-form oscillograms were also taken on customer load and on the system voltage. These oscillograms are not reproduced here, but they show that the original wave form was bad, and that the synchronous condenser was effective in improving this wave form to the extent that it should cause no telephone interference. It is also interesting to note that the lighting load was reconnected to the main 13.8-kv supply on October 27, 1938, after the condenser was placed in service and that satisfactory operation of the sensitive mercury-vapor lamps is now obtained from that source. It had been impossible to operate these lamps satisfactorily from the 13.8-kv source before the installation of the condenser.

Cost and Benefits

The installation of this synchronous condenser was not particularly cheap. However, the total cost was under $10 per kilowatt of integrated maximum demand. This cost is considered reasonable

when it makes possible the supply to such a load without noticeable disturbance to other customers. In addition to its primary function of correcting the voltage flicker, the condenser is desirable for the following reasons:

1. Excessive maintenance of the transformer tap-changers is eliminated.

2. The load power factor is corrected to approximately unity.

3. Transmission losses are reduced.

4. The stability limit of the 132-kv system is raised.

5. The Dixon load can be carried from Powerton or Waukegan alone, without running Dixon steam generators, if one 132-kv line is out.

Conclusion

The installation of a suitable synchronous condenser proved to be an excellent remedy for voltage flicker caused by severely fluctuating load on a 132-kv overhead transmission line. The cost of the remedy at $10 per kilowatt of arc-furnace load was more than justified because it resulted in better system operation, in addition to making the supply to this class of business possible, without disturbance to other customers. This type of load, while it has wide instantaneous swings, has a very satisfactory load factor throughout the 24-hour period. Such loads should be encouraged by power companies.

Discussion

W. B. Wallis (nonmember; Pittsburgh Lectromelt Furnace Corporation, Pittsburgh, Pa.): It is noted with interest that the furnace load in question consisting of two high-power rolling-mill-type electric furnaces rated at six tons each are connected to the center of a 220-mile 132,000-volt 60-cycle transmission line, along with various power and lighting loads and the lighting voltage flicker has been neutralized.

As the author states, arc-melting-furnace load of this character is one of increasing importance as a matter of large revenue to the power companies and is interesting in that it shows an economical solution of voltage fluctuation due to the results of high peak loads on a very long transmission system serving many small lighting communities.

These furnaces while rated at 7,500 kva each, are habitually overloaded and are frequently run with a load of 16,000 kva each. While they were rated at 6 tons they regularly make heats ranging from 22 to 24 tons. The installation of the furnaces in this plant is a distinct commercial success, making high-grade steel ingots from ordinary country scrap at a price well below the established market for billets of similar size. Indeed the demand for the steel has been such that the furnaces have necessarily been enormously overloaded to get out the necessary production.

The power bills for this customer's 18,000 to 19,000-kw load average $40,000 to $44,000 per month which constitutes a very attractive source of revenue to the power system.

The more than 100 per cent furnace overload naturally imposed conditions on the power company that were not originally considered in the power service calculations. The installation of the 20,000-kva synchronous condenser with its voltage regulator is an ingenious and interesting installation, and the fact that this together with the switchgear and reactors has resulted in an entirely satisfactory solution of the difficulties originally encountered is a subject for congratulation to the engineers who conceived and carried out the work. This is especially true in view of the fact that the cost was very moderate and the remedy so complete and all under very unusual conditions caused by the extra long length of transmission line.

The commercial success of this plant will no doubt result in the installation of a number of other similar arc-furnace rolling-mill plants and the solution will unquestionably be of interest to prospective suppliers of such large load and revenue.

It might also be noted that if a separate line had been run from Dixon to Sterling to carry the lighting load that perhaps no very great objection would have been found to the furnace load, even though much larger than originally considered due to the unusually large overloads imposed.

The power-factor conditions are quite satisfactory for the load in question, as is also the load factor, all of which will no doubt encourage other installations of a similar character.

Sterling Beckwith (Allis-Chalmers Manufacturing Company, Milwaukee, Wis.): Mr. LeClair's paper is very interesting and shows the logical solution of a difficult problem. As a machine designer I would like to emphasize the utilization of saturation in the condenser to improve its characteristics for this application. When saturation of transient reactance is ordinarily thought of, the saturated value, or what has more recently been called the rated voltage value, is taken as the effective value for a dead short circuit from rated voltage. This rated voltage value has developed for use in studies of system short-circuit currents. However, for a case such as the one discussed by Mr. LeClair, the value of transient reactance that should be used to calculate the transient voltage dips is a value which is more saturated than the rated-voltage value used in studies of short-circuit currents. The reason is that the machine is initially operating at half to full load, so that the internal voltage of the machine is greater than unity.

Mr. LeClair gives the rated voltage saturation factor as 0.91, and the saturation factor effective at full load during small voltage changes as 0.67, which shows the pronounced gain from saturation. It also shows that ordinary characteristics of an alternator, such as short-circuit ratio, synchronous impedance, or even rated-current or rated-voltage values of transient reactance will not give a direct measure of the stability of a machine for service such as that described by Mr. LeClair.

It would be interesting to know the per unit resistance of the system plus transformers plus reactors, since this resistance is one of the important factors contributing to the hunting that was observed when 40 per cent reactance was used. It might also be interesting to know the relation between the peak load at the Sterling bus and the steady-state power limit at this bus, both with and without the 20 per cent and the 40 per cent reactors.

Figure 1 accompanying this discussion shows the connections used to test the voltage dip of a large condenser under sudden load changes starting from an initial condition of full load. Curves taken from oscillograms made during such a test are shown in figure 2 of this discussion.

Curve A is the per unit voltage, and curve B is the per unit current. It should be noted that both contain a subtransient portion lasting about 0.05 second and a transient portion which lasts beyond the end of the oscillogram. The third curve of this figure shows the ratio of the change in voltage to the change in current, or in other words the reactance effective during the voltage change (since $R = E/I$). The subtransient and transient effects are even more pronounced in this curve than in the others. For purposes of comparison, the test values of saturated and unsaturated reactances are shown by arrows. These test values were obtained by sudden short-circuit from no load, and the saturated values correspond to short-circuit at an initial voltage exactly equal to the internal voltage (= voltage behind Potier reactance) existing in curve A prior to the sudden change in load. The change from a subtransient to a transient to a saturated synchronous reactance is so striking and clear that further comment is unnecessary. Also the agreement with the actual numerical value of the reactances as deter-

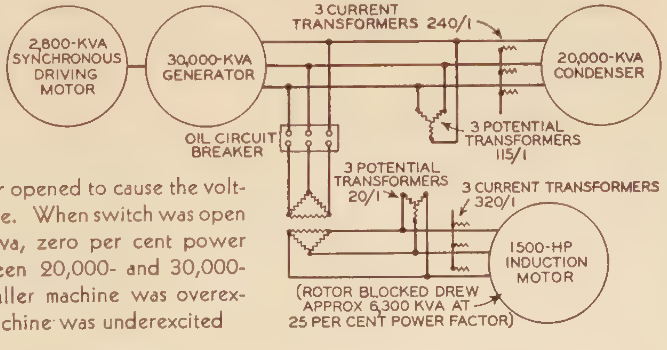


Figure 1. System on which tests were made

Oil switch was closed or opened to cause the voltage to suddenly fall or rise. When switch was open approximately 10,000 kva, zero per cent power factor, circulated between 20,000- and 30,000-kva machines. The smaller machine was overexcited, and the larger machine was underexcited

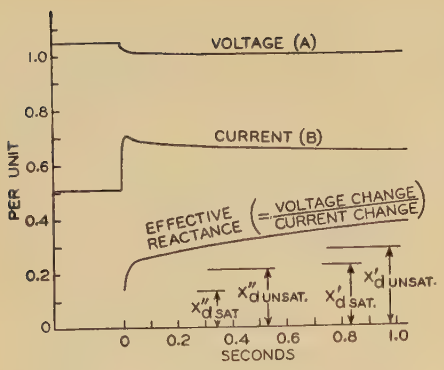


Figure 2. Results of voltage-dip tests

mined by usual methods and here shown by the arrows is very good.

B. M. Jones and **V. E. Hill** (nonmember; both of Duquesne Light Company, Pittsburgh, Pa.): We electric utility people had just as well recognize that large electric furnaces are part of our business—some of our bread and butter—and we must make up our minds to learn how to handle them so that we can live more peacefully.

As we all know, the difficulty in serving large electric arc furnaces is that the large load swings at low power factor may cause objectionable voltage fluctuations to other customers in the same area, and expensive corrective measures may have to be taken.

Obviously, the correct engineering approach is to determine in advance what the power swing and resultant flicker will be, and to provide a suitable system connection and corrective equipment, if necessary, to keep the flicker within tolerable limits. However, this is not always so easy, for in some cases it is very difficult, if not impossible, to find out just what the electric performance of the furnace will be, due, we believe, to the fact that the manufacturers of the furnace cannot determine themselves in advance the exact electrical performance and characteristics of the complete furnace installation.

In a recent installation, certain system changes and switching during the meltdown period were necessary after the furnace installation was made, to prevent the flicker from being reflected into parts of our system where it would be objectionable. This furnace caused much larger swings than had been anticipated as a result of our experience with other furnaces and from what we had been led to believe would exist as shown by literature on this subject. Tests of these swings, both by recording meters and oscillograph, indicated frequent single-phase swings of 300 amperes, with a maximum of 400 amperes, which is equivalent to 8,500 kva or, for such currents in all three phases, is equal to 14,000 kva, three phase. The 22-kv supply voltage at this station fluctuated as much as four to six per cent, with occasional variations as high as eight to ten per cent. These fluctuations were also experienced, of course, at other customers and distribution stations in this vicinity, while there was a two to three per cent voltage fluctuation on the 22-kv bus of the transmission supply substation.

The higher fluctuations on the 4-kv distribution substations within the vicinity of this customer gave rise to a few flickering-light complaints, in the order of four or five a month, which is remarkably small in view of the magnitude of the swings and the thousands of customers exposed. However, another objection to these voltage fluctuations from a company standpoint was the excessive number of regulator operations caused thereby. Counters placed on some of the regulators in nearby distribution substations indicated that, whereas only 4 to 6 operations per hour were experienced when the furnace was not running, from 200 to 300 operations per hour occurred when the furnace was on, that is, during the melting-down period. A maximum of 1,000 operations per hour was noted on one occasion; this based on only a 15-minute period.

Other distribution substations fed from this same transmission substation, but not by the same lines feeding the furnace, also experienced an increase in regulator operations, but not nearly so many. Checks on one regulator indicated 50 to 150 operations per hour with the furnace on, whereas the normal number with the furnace off was generally less than 30 per hour. Obviously, such an increase in regulator operations would enormously increase the maintenance on them.

Even though the number of complaints was relatively few, it was evident that something had to be done. One or more new 22-kv lines into this area were considered, but needless to say, the cost would have been entirely unjustified, as would also have been the installation of a synchronous condenser. Since the voltage fluctuations back at the transmission substation were tolerable, the obvious solution would have been a separate line to serve this furnace only, but this, too, would have been very expensive. However, the same objective was accomplished by another means. Since this customer was the first load fed from his direct line, supervisory equipment was installed so that the breaker at his station could be opened by remote control from the transmission substation, thus leaving him fed radially on this one line. This move was accomplished at a cost of only $4,400.

It is true that the opening of this breaker reduces the normal capacity to this area, or rather the number of feeds to this district, since the customer's load utilizes a good portion of the normal line capacity. The breaker is only open a very small percentage of the time, because the furnace is not operated continuously—generally, only 15 or 20 heats a month and not more than one a day. Furthermore, the breaker can be instantly closed and the line returned to service in this district during any emergency periods, such as arises during lightning storms or for failure of other lines in this district. Should this customer ever operate the furnace continuously, one or two shifts each day, or if the load in this district should materially increase, then another line or two would be needed and could then probably be justified.

As concerns the enormous number of regulator operations, the breaker opening described above reduces the severity of the voltage fluctuations of the stations in the vicinity of this customer to that experienced at the supplying transmission substation, two to three per cent. Even these fluctuations were objectionable and so our substations department developed a time-delay device to attach to the regulators. These devices permit of the normal functioning of the regulators to adjust for bus-voltage variations, load changes, and the like, but prevent the regulators from attempting to follow the rapid fluctuation caused by the furnace.

We have conducted negotiations from time to time on other large furnace installations, up to 10,000 and 12,000 kva, in which we considered service at 66 kv, and also the use of corrective equipment, such as referred to in Mr. LeClair's paper.

It has also been our experience that the size of the power swings caused by electric arc furnaces is subject to appreciable control by the furnace operator, through the choice of the voltage tap used, the length of arc, and general skill developed from experience.

The electric utilities should, we believe, protect themselves from these objectionable voltage flickers when they interfere with the service to other customers, probably by charging against the furnace job the expense of major system rearrangement, new lines, or corrective equipment, all of which may be necessary to hold fluctuations within tolerable limits. In this connection, it is highly desirable and has been our experience, that it is to the mutual benefit of all concerned for the utility, customer, and furnace manufacturer to co-operate and work together in the initial design and in the operation of the furnace.

L. W. Clark (The Detroit Edison Company, Detroit, Mich.): Most power companies at some time or another have encountered similar service problems involving electric arc furnaces as that described and thoroughly analyzed by Mr. LeClair. There are always several ways in which the load can be handled and it is usually a matter of economics as to which method is finally selected. This installation is of particular interest in that the analysis shows a synchronous-condenser installation to be the most satisfactory solution.

In general, our experience has indicated that a synchronous condenser would not improve a flicker condition sufficiently to warrant the installation from the standpoint of flicker elimination alone. There usually had to be some other need for the condenser, such as general voltage control of that part of the system before its installation could be justified. No doubt these other advantages were deciding factors in the selection of a condenser for this particular installation. The original flicker condition was not beyond the range of correction afforded by the condenser operation as shown by the reduction of flicker from 3.6 per cent to 1.5 per cent.

Where the voltage fluctuation or flicker must be corrected to a greater extent, for instance, in the range of eight to one, it is doubtful if a condenser installation would prove economical as compared with a motor generator set. As an example, an installation of two small single-phase arc furnaces at Vassar, Mich., as shown in figure 1, illustrates both the motor-generator-set and the synchronous-condenser method of solution. The smaller furnace rated 250 kw, 360 kva, has maximum instantaneous load fluctuations of about 500 kva, and was

served from the 4,800-volt synchronous-condenser bus. Calculated voltage fluctuations on the 4,800-volt bus due to the furnace operation are 4.8 per cent with the condenser shut down, and 3.2 per cent with the condenser operating. This is a standard design of synchronous condenser with a subtransient reactance of 24 per cent and a synchronous reactance of 164 per cent. Taking into account that there is no buffer reactor to force the condenser to absorb more of the reactive kilovolt-amperes, the reduction in voltage fluctuation is of about the same order as that of the Sterling installation described by Mr. LeClair. As long as there was no general lighting load served from this bus, the voltage conditions were satisfactory as the flicker in the main 24-kv bus was not objectionable under normal operating conditions with both 24-kv lines in service. However, it later became necessary to transfer lighting load to the 4,800-volt bus and then, even with the condenser in operation, the flicker proved annoying and caused the furnace load to be transferred to a motor generator set on the other bus.

The motor generator set consisting of a 1,750-kva 80-per-cent-power-factor synchronous motor driving a 600-kw generator was originally installed to handle a 600-kw 875-kva single-phase furnace which has maximum load fluctuations of about 1,300 kva, or about $2^1/_2$ times those of the smaller furnace, and would cause a flicker of about 12.5 per cent on the bus if corrective measures were not applied.

It is obvious that a condenser installation of sufficient size to reduce the 12.5 per cent flicker to something in the order of 1.5 per cent to 2 per cent, would not only be expensive but it would also be of much greater size than could ever be used or needed for general voltage control of that portion of the transmission system. However, the motor generator set, which has a slightly lower installed cost than the 3,000-kva condenser on the opposite bus, does reduce the flicker to less than 2 per cent, and tests show the set to be about $5^1/_2$ times as effective in flicker reduction as the more costly 3,000-kva condenser.

The paper mentions the fact that for a load with a very short-time characteristic, such as a resistance-welding machine, a motor generator equipped with a flywheel and using an induction motor is satisfactory but that for a furnace load with the greater load factor, the flywheel would be of no benefit. It is our opinion that we might go a step farther and state that a flywheel set need only be considered on loads with a high fluctuating kilowatt demand, such as rolling-mill loads, but that for either welder loads or arc-furnace loads in which the predominating source of trouble is the rapid change in reactive rather than kilowatt load, the flywheel type of set is not generally needed. A straight, synchronous set will do a very good job where the desired reduction in magnitude of voltage fluctuation is not greater than five or ten to one.

It is interesting to note that the furnaces apparently operated for some time prior to the condenser installation and, consequently, imposed annoying flickers on the 132-kv system which would affect the local lighting load at Dixon. While these flickers, no doubt, only occasionally reached the maximum value of 3.6 per cent, there probably were frequent flickers of sufficient magnitude to affect the lighting, and we would be interested to know if many customer complaints were received during this period.

H. P. St. Clair (American Gas and Electric Service Corporation, New York, N. Y.): Mr. LeClair has described in his paper a truly difficult problem of voltage regulation. Problems of this type are encountered now and then, probably with increasing frequency as time goes on, and Mr. LeClair's paper describing the solution in his particular case will undoubtedly be of value to many other engineers faced with the necessity of working out voltage regulation problems of a similar nature in the future.

I should like to describe briefly a somewhat similar problem which was encountered on the system with which I am associated and the solution which was used to take care of it.

At St. Joseph, Mich., the Auto Specialties Manufacturing Company, operators of a foundry and a machine shop, had installed several electric furnaces, one of which was nominally rated at 5,000 kva, but actually used at a much higher rating. This customer's load, including the large furnace, was supplied over a separate double-circuit 27-kv line from the Riverside substation which in turn was supplied by a 37,500-kva transformer bank, stepping down from a double-circuit 132-kv line 38 miles in length from the Twin Branch generating plant and substation. This transformer bank was equipped with a tertiary winding to which was connected a 15,000-kva transformer condenser arranged to regulate voltage on the 27-kv bus. In addition to the Auto Specialties Manufacturing Company's circuits, this substation also supplied a 27,000-volt system, including the cities of Benton Harbor and St. Joseph.

This arrangement was expected to be entirely adequate to handle the fluctuating industrial load in this area without difficulty and as a matter of fact for several years voltage fluctuations did not become critical. However, as the Auto Specialties Manufacturing Company's operations increased, accompanied by more intensive use of the large electric furnace, severe voltage fluctuations were encountered in the adjacent area supplied from the Riverside substation 27-kv bus. Observations at this time indicated that the electric-furnace load was imposing on the system swings as high as 15,000 kva, the increments in these swings being largely reactive kilovolt-amperes. Visible fluctuations of four to five volts were observed on the Riverside substation 27-kv bus, with nearly two volts visible on the 132-kv bus. Obviously, the synchronous condenser offered very little help since the power swings were entirely too fast to be followed by any condenser and regulation scheme.

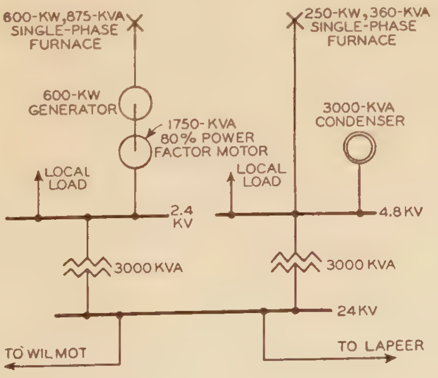


Figure 3. Vassar substation

Since the power and reactive kilovolt-ampere swings were actually producing voltage fluctuations in excess of five volts, it seemed almost obvious at the outset if we were to continue to serve this customer's load, a different arrangement would be necessary. Calculations indicated that a separate transformer, stepping down from 132 kv to 27 kv to supply this customer's lines alone would reduce fluctuations on the 132-kv bus to less than two volts; and with the synchronous condenser operating on the 27-kv bus from which the remainder of the system load was supplied, the regulation on that bus would be still better than on the 132-kv bus. Consequently, a new 15,000-kva transformer bank was installed and the heavy swings of this particular customer were as you might say "quarantined" in this manner, so that service could be supplied to the remaining area without intolerable voltage fluctuations.

Comparing this setup with that described by Mr. LeClair and illustrated in figure 2, of his paper, it might be pointed out that Mr. LeClair was fortunate in having the local distribution load at Dixon supplied directly from the 132-kv system, so that he was not faced with the problem of supplying any other load except the customer's load from the low side of the transformer bank at Sterling. In effect, the solution which we adopted was to change over to a system more nearly like that shown in figure 2 with the local distribution system separated from the furnace load.

G. B. Schneeberger (Cleveland Electric Illuminating Company, Cleveland, Ohio): Mr. LeClair's paper is a very interesting and detailed description of the problems arising in connection with the operation of an arc furnace especially when the furnace is used to melt cold metal.

This type of load is inherently very erratic and demands careful consideration before it is connected to any system, or overworked regulators and flicker complaints will result.

The great improvement in refractories has enabled operators to push their furnaces far beyond their original capacities. This has resulted in an insistent demand for more power. The nominal rating of a furnace is on a par with the nominal rating of welders. It is not uncommon to encounter furnaces which have doubled their original transformer capacity. In one case on our system, a furnace whose original transformer equipment was 375 kva is now operating with 1,200 kva.

This emphasizes the necessity of allowing a liberal margin when this type of load is under consideration.

It is interesting to note the application of the synchronous condenser in handling the unusual *lagging* reactive kilovolt-amperes. With the advent of the modern strip mill, due to the liberal use of synchronous motors, troublesome *leading* re-

active kilovolt-amperes was encountered. The synchronous condenser was also used to advantage to correct this condition. Most of the more modern mills are now provided with regulators which control the reactive condition at its source.

E. S. Fields (Cincinnati Gas and Electric Company, Cincinnati, Ohio): The AIEE paper entitled "Arc-Furnace Loads on Long Transmission Lines" has been read with a great deal of interest. The various solutions considered and the one finally adopted along with the special characteristics of the synchronous condenser are to my mind distinct contributions in the field of electric-system engineering.

From my knowledge of the rate per kilowatt-hour to make electric melting attractive and the large amount of system investment to serve this customer, it is quite apparent that the customer must have a very high annual load factor to make the service mutually attractive financially. I imagine that some of the five items of benefits listed in the paper were substantial, particularly item 5 which represents a release of transmission capacity, and that the evaluation of these items went a long way toward justification of the expenditure.

While we have no such problem, as the one you describe, on our system, we have one that has some of the same elements in which you may be interested. It is a large steel rolling mill located about 40 miles from our power stations and served from 66-kv lines which also supply the usual types of system load at the same locations. The variations in the steel-mill load are as much as 25,000 kw in a short interval of time and, since a great part of this load consists of synchronous-motor-driven motor generator sets, automatic field control has been applied to these motors to vary the field strength with the load. The application has given entire satisfaction.

T. G. LeClair: Mr. Wallis has offered some valuable additional information on the characteristics of these particular electric furnaces. The characteristic which he mentions of severe overloading has been found to apply to not only this furnace installation, but also to a large number of others. The statement made by Mr. Wallis that there would have been no objection to the furnace load if the lighting load had been on a separate line is not quite correct. He has evidently been misinformed, because the lighting load at Sterling was connected through separate lines to the Dixon 33-kv bus during the time of greatest disturbance. The original disturbance was, in fact, noticeable throughout the territory served from the Dixon substation.

The comments by Mr. Beckwith are an important contribution from the designer's viewpoint. They show that with a reasonable foreknowledge of the problem much can be done to adjust a synchronous condenser to be more beneficial in handling of disturbances caused by fluctuating loads. In answer to his question, the resistance of the system to the condenser bus is 1.3 per cent on a 20,000-kva base with either a 20 per cent or a 40 per cent reactor. The system's reactance to the condenser bus is 42 per cent and 62 per cent with the 20 per cent and 40 per cent reactors, respectively.

Mr. Beckwith's question concerning the steady-state power limit at the Sterling bus is quite pertinent. The calculated pull-out limit is 32,000 kw with 40 per cent buffer reactor, 47,000 kw with 20 per cent buffer reactor, and 90,000 kw with no buffer reactor.

The discussions by Mr. Clark and by Messrs. Jones and Hill show radically different solutions for the intermittent-load problem. In both of these cases the synchronous condenser described in the paper would not have been the most satisfactory solution. The size of the loads, their location on the system, and the annual load factor all apparently had a bearing in coming to a different conclusion.

Messrs. Schneeberger and Fields both point out that intermittent loads are frequently associated with synchronous machinery and in this case the regulating value of the synchronous machinery can be taken advantage of without any additional cost for a special condenser installation.

Mr. St. Clair's discussion, surprisingly enough, indicates that another furnace installation called for a rather similar solution, even though the problem was approached from the opposite angle of having the condenser already in service and installing the line to make the condenser more useful.

The variety of solutions for the problem of intermittent loads which have been mentioned in the discussions accentuate the note on which I would like to close this discussion. That is that every intermittent load appears to have certain special characteristics and is applied to a power supply system with different limitations. Therefore, there appears to be no general answer to the question of what is the best method of supplying these intermittent loads.

Intermittent equipment is a growing essential tool to the industrial user. Unquestionably, the power companies should stand ready to supply these intermittent loads. The greatest benefit can be obtained by whole-hearted co-operation between the equipment designer, the equipment user, and the utility company *before* the order is placed. Adjustments in the design of the equipment or the proposed methods of operating may frequently result in lessening the possible disturbances to the point that the intermittent equipment can be installed without expensive special facilities to be paid for either in the rate or as a separate charge.

Mercury-Arc Rectifiers in the Coal-Mining Industry

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ALTHOUGH mercury-arc rectifiers at present constitute only a small part of the total installed capacity of a-c to d-c conversion equipment in coal mines, in the past three years 21 rectifiers of a total rated capacity of 8,100 kw have been placed in service in 15 coal mines. Considered alone, this would not be important, but, since these rectifiers exceed in number of units and capacity other forms of new conversion equipment installed in the same period, a definite trend toward the use of rectifiers is indicated. It is the purpose of this paper to discuss the causes for this trend and to record, in so far as it is possible, the results which have been obtained with rectifiers in mining service.

Two developments are responsible for this interest in rectifiers. First is the increasingly rapid change from hand loading methods to concentrated operation with machine loading. If the large investments in mining machines required for mechanical mining are to be profitable, these investments must be backed up by a power supply which is efficient and which is adequate to supply an uninterrupted flow of power to the mining machines.

The second is the development of the ignitron rectifier which can be used advantageously for 275-volt service and for higher voltages. Prior to 1936, only the tank-type or multianode rectifier was available for which the principal field of application is at 500 volts and higher. Since, by far, most of the coal is produced by 275-volt mines, it was not until the ignitron was developed for large capacity that rectifiers really became available to the coal-mining industry as a whole.

The beginning of the modern trend to rectifiers is marked by the installation of a 600-kw 600-volt tank-type rectifier by Pittsburgh Coal Company in August 1936. This was discussed by A. Lee

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Barrett at an AIEE District meeting in Akron, Ohio, in October 1937. Briefly, Mr. Barrett stated that this unit is saving 26.5 per cent of its cost per year due to increased efficiency. The rectifier serves a mine working three shifts per day and 600 shifts or more per year.

The year 1937 saw two installations which produced several "firsts". In February, the Union Collieries Company of Pittsburgh placed a 300-kw 275-volt d-c, 2,300-volt three-phase 60-cycle ignitron equipment in an underground station, approximately two miles from the shaft bottom. This equipment may be briefly described as consisting of an automatic control, an Inerteen-filled transformer, a six-tube ignitron rectifier, and a water-to-air heat exchanger for cooling the rectifier. Because of clearance conditions in the main haulage way, the maximum height of any part is 55 inches, and the maximum width 62 inches.

In October 1937, the Weirton Coal Company installed three portable ignitron rectifiers to be the first mine:

1. To be served solely by rectifiers.
2. To use portable rectifiers.
3. To make all their substations portable.
4. To place all their conversion equipment underground.

This equipment is essentially the same as the Union Collieries Company equipment, except that it is mounted on three trucks. The transformer and a-c switchgear are on one truck, the rectifier and its auxiliaries and the heat exchanger on the second, and the d-c switchgear on the third.

Installations in 1938 followed essentially the pattern established in 1937.

In 1939, two noteworthy advances have been made. Three 600-volt ignitron rectifiers have been placed in service, all of these being of the nonportable type in surface substations.

The second innovation, which may be the more important, is the use of permanently evacuated, permanently sealed ignitrons. One 200-kw 275-volt equipment and three 300-kw 275-volt equipments have been placed in service at the date of reading this paper.

The principal advantages of the rectifier are, of course, high momentary overload capacity and high efficiency, and these advantages have, in many cases, combined to make the rectifier the most economical conversion unit.

In a typical example of concentrated mechanical mining, a substation is located adjacent to the load center and serves several operating units, each unit consisting of a cutter, a loader, and a locomotive. These machines are powered by intermittent or short-time-rated motors, which have continuous ratings averaging about one-third of the nominal ratings. A substation to serve this group of machines should have sufficient continuous capacity to furnish all the power that the machines can safely absorb on an all-day basis. The substation should also have sufficient momentary capacity to carry over the normal peak load without damage to the conversion unit or interruption of the supply of d-c power. Experience has indicated that this peak frequently approaches the sum of the combined rated currents of all the machines served.

For example, a substation serving six units, having a total of approximately 960 horsepower, should be capable of carrying 900 kw momentarily and 300 kw continuous. Interpreted in terms of conversion units, this means a 300-kw rectifier will operate with fewer outages than a 400-kw rotating machine, since the 300-kw rectifier unit can carry more load momentarily than the 400-kw rotating unit.

At 275 volts, there will be but a minor difference in the cost of the substation including building, foundation, and installation, whether a rotating machine or a rectifier is used, and at 600 volts, the rectifier will definitely be less expensive. Any saving in operating cost obtained by the use of the rectifier will be a net gain.

Basing a power-cost comparison on 275-volt equipment only, the losses of a 300-kw rectifier will average 5 kilowatt-hours per hour less than the losses of a rotary converter over the usual load cycle, and will average 20 kilowatt-hours per hour less than the losses of a synchronous motor generator.

In a mine in which power must be kept on the trolley continuously to operate pumps and other auxiliary services, the annual saving in comparison with a rotary converter will be roughly 40,000 kilowatt-hours, which at a rate of one cent per kilowatt-hour amounts to $400. The comparison with a motor generator shows a saving of 160,000 kilowatt-hours or $1,600 per year.

The savings in 600-volt service are more impressive, since, on the higher voltage, the rectifier efficiency is increased approximately three per cent, while the efficiency of 275- and 600-volt rotating machines are approximately the same.

As of this date, six ignitron rectifiers have each had more than one year of service, the maximum in this group being 32 months and the average 22 months. Nine additional ignitron rectifiers have had less than one year each, the maximum in this group being 9 months and the average 6 months.

In the six equipments of the first group, there are 36 ignitron tanks, 36 excitation thyratrons, 36 ignitor crystals, 6 vacuum pumping systems, and 6 cooling systems. These are the parts which were really on trial in the earlier installations.

No delays have been caused by leaks in the vacuum system and only one shutdown has been caused by any type of failure of the vacuum system. This was caused by improper operation, contrary to instructions. When the mercury was replenished in the mercury-vapor pump and attention was called to the proper method of operation, the trouble was cured permanently.

Four ignitor crystals have been replaced in the field. Two of these were defective crystals which failed very shortly after installation. Two others, which were replaced after approximately one year of service, were not returned to the factory for inspection, so the exact condition of these crystals at the time of reported failure is unknown.

The minimum life of firing tubes has been slightly more than 12 months. Some firing tubes have been in service two years, but the average is at least 15 to 18 months.

Only four of the ignitron tanks have been opened, all for replacement of firing crystals. No other internal parts have been replaced or repaired.

There have been no recent failures of the cooling system. In several of the earlier installations, it was necessary to modify the circulating-water pumps to prevent loss of water and to improve bearings. These modifications have, apparently, eliminated the trouble. Under present conditions, the amount of water required to replenish losses is negligible.

It seems evident, therefore, that ignitron rectifiers, at the present stage of their development, are highly reliable, comparing favorably with rotating machines. The cost of maintenance is extremely low except for the cost of replacing firing tubes, which, judging from existing experience, should average less than $150 per year. In comparison with rotating conversion machines, the over-all cost of maintenance of rectifiers will usually be higher, but the difference should not exceed $100 per year on the smaller ratings. On the larger ratings, maintenance costs will be more nearly equal.

In an analysis of power conditions at a mine, due consideration should be given to the effect of added equipment on the

power factor of the system. A rectifier, with its transformer, operates at an average power factor of approximately 93 per cent. A rotary converter is usually adjusted to operate at unity power factor at the average load, but as an all-day average, will usually operate at something less than unity, lagging. Standard mining motor generator sets are capable of producing a large corrective effect to compensate for inductive equipment on the system. A power-factor analysis can be made only with a full knowledge of local conditions and any further attempt to make a definite statement on this subject would be useless.

As a result of three years' experience in the application and operation of rectifiers in coal-mining service, combined with many years of experience in other industries, we can summarize as follows:

1. Rectifiers are at least equal to other types of conversion equipment in reliability.

2. For equipments of equal service capacity for mining conditions, the installed cost of a rectifier will be approximately equal to or less than the cost of rotating conversion equipment.

3. The operating cost of a rectifier, including maintenance and cost of power, will be less than the operating cost of rotating machines, except where power-factor correction is of considerable importance.

4. Where additional power-factor corrective equipment is necessary, a motor generator, or a rectifier with capacitors may be the preferred type of equipment.

5. An analysis of local conditions, taking into account required service capacity, hours of service per year, power cost rates, and power factor, is necessary to establish which type of conversion equipment is most advantageous.

Discussion

F. L. Kaestle (nonmember; General Electric Company, Schenectady, N. Y.): This paper on "Mercury Arc Rectifiers in the Coal-Mining Industry" is indeed very timely, and is of interest to the entire electrical field, as well as the coal-mining industry.

Mr. Renshaw has very well pointed out that the rapidly expanding mechanization of coal mining has led to an increased interest in rectifiers, because their characteristics are so well adapted to the type of load encountered in this service.

The increased average power load of the mechanized mine has required the installation of more conversion equipment. The fact that the load center is highly concentrated in a relatively small working area, and that this area shifts quite rapidly as the coal is worked out, has increased the need for readily movable underground substation equipment. The development of the ignitron has made it feasible to build portable rectifiers to meet this important shifting-load condition.

The important characteristic of the mine load which makes rectifier equipment particularly adaptable, is that the load fluctuates widely. The cutting and loading machines and the haulage locomotives produce alternately high peaks and light loads during the working shift. Also the trolley usually must be kept energized continuously between shifts, with only the very light load of maintenance and inspection work, and for pumps and lights. The high percentage of very light load periods emphasizes the most outstanding advantage of the rectifier, that of low no-load losses which account for its high efficiency at light loads. As an example, the no-load loss of a 300-kw ignitron rectifier equipment is approximately 4 kw, that of a rotary equipment 12 kw, and of a motor generator 26 kw.

Mr. Renshaw has demonstrated the savings effected by these lower rectifier-equipment losses for a mechanized mine operating 600 shifts per year. This number of working shifts is quite high as an average, and even here the power savings are substantial. For mines working 200 to 300 shifts per year, and there are a large number which do so, the savings are even greater.

High overload capacity must be considered in the design of any equipment for mining conversion, but the means by which it is accomplished are decidedly in favor of the rectifier substation. The continuous rating and hence, to some extent, the physical size of any conversion equipment to carry a high-peak, low-average load can be kept to a minimum if that equipment has a high momentary peak capacity. Even with a rectifier substation, it must be remembered that the rectifier unit itself must still be selected primarily on the basis of the maximum load to be carried. However, the transformers, cooling equipment, and switchgear may be selected primarily on the basis of the continuous rating, and these parts make up a large part of the total equipment. Hence, the high overload capacity can be obtained in the rectifier equipment without the large increase in copper and iron required to obtain it in rotating machines.

One of the principal considerations in the development of the ignitron was to improve the efficiency for application in the 250–275 volt field. In order to reduce the arc drop it was necessary to place each anode immediately above and very close to the cathode. This was accomplished by enclosing each anode with its individual mercury-pool cathode in a separate vacuum tank or tube. These single-anode units are assembled as a group to form a rectifier unit. With such an arrangement, it is necessary for practical design reasons, to initiate the arc each half cycle by means of an ignitor, rather than maintain it continuously, as is done in the multianode rectifier. Thus the real operating difference in the two types lies mainly in the ignition systems used, for the basic rectifying principles of the two are the same.

The mechanical construction of the ignitron has served to simplify the rectifier. The low height and light weight of the individual units now make it practical to build portable and underground equipments. The mercury pool does not have to be insulated from the vacuum tank, in the ignitron, and so a sturdier design results. This simplification of the ignitron, together with its improved efficiency, has expanded the use of the rectifier into many new low-voltage fields, including this important coal-mining industry.

Another progressive step, mentioned by Mr. Renshaw, which has permitted the further simplification of the ignitron, is the use of permanently evacuated, sealed tubes. With these tubes, no vacuum-pumping system and no auxiliary equipment to indicate or control vacuum is required. The reliability of the sealed tube, from the standpoint of continuity of service, has been well established by tube equipments for welding machines, synchronous-condenser exciters, and building lighting, as well as by three coal-mining equipments which are now in service.

The lower installed cost of the sealed-tube equipment and the lower maintenance, due to the elimination of vacuum equipment, must be balanced economically against tube renewal costs, and this resolves itself into a question of tube life. Since the tube is constructed of corrosion-resisting materials, its life is dependent on vacuum and ignitor life. Many tubes in welding service have been operating for over four years and are still in service. Although it is too early to know what tube life is in this service, on the basis of very encouraging results so far, it is confidently expected that the tubes will last from three to five years or longer. When their life has been demonstrated, the sealed-tube rectifier will be the most attractive equipment available in ratings of 300 kw and less, where the cost of the pumping equipment is a relatively large item.

Rectifiers have been very successfully applied in 500-volt services for many years and now, with the development of the ignitron, the many operating advantages of the rectifier are available in the 250-volt field. The low light-load losses of the rectifier are its strongest point. The ignitron is simple, sturdy, and reliable. It is easily made portable, and is well suited to underground operation. Rectifier substations are easily provided with high momentary overload capacities. Because of the absence of rotating machines, the rectifier substation equipment is practically immune to damage from lightning.

The sealed-tube ignitron not only retains all the other advantages of the pumped equipment, but also offers a means of reducing the installed cost and maintenance for the ratings to which it is suited.

With the present increase in coal production, the mercury-arc rectifier should play an ever more important role in the reduction of mine operating costs.

D. E. Renshaw: I am very glad to have heard Mr. Kaestle's contribution on this subject, particularly his discussion regarding the permanently sealed ignitrons.

It is quite evident, because of increasing mechanization of mines, additional conversion equipment will be required. It is also undoubtedly true that there are many conversion units still in service which, because of age and long use, are expensive to maintain and are wasteful of power. For this added and replacement conversion equipment, the ignitron rectifier will, in many cases, provide a better source of d-c power at a saving in over-all cost.

New Type of D-C to A-C Vibrator Inverter

O. KILTIE
ASSOCIATE AIEE

VARIOUS SYSTEMS have been devised to operate from direct current to supply alternating current at specified frequencies for specific loads. However, there have been the usual limitations to prevent individual extensive application of each type.

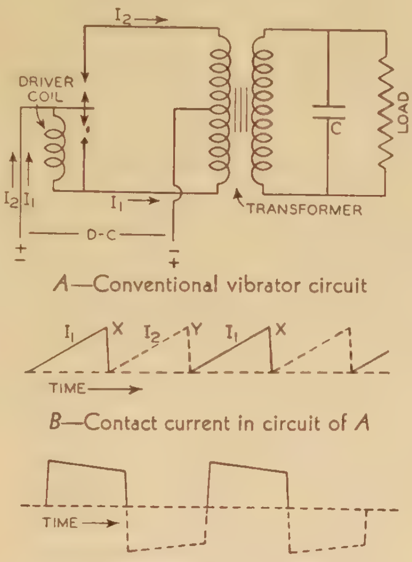
Motor generator and dynamotor type machines do not fill all the requirements for universal needs. Special provisions must be made to obtain good frequency regulation and high efficiency.

Grid-controlled vacuum-tube inverters have been successful for many purposes, but for loads in the lower ranges, the high cost and low efficiency are objectionable. With supply voltages in the order of 6 or 12 volts direct current the normal arc or plate drop of the tube itself may be as much as the supply voltage leaving nothing for the load. Practically instantaneous attainment of rated frequency during the starting period would be an advantage for this type.

Vibrator-type inverters have been extensively used during the last few years, especially in the automobile-radio field where load requirements have not been severe and long contact life has not been a fundamental requirement. Their use has increased considerably of late for various purposes such as for electric clocks, small motors, musical instruments, and various electrical control equipment.

It is the purpose of this paper to present to the industry a form of vibrator inverter for the conversion of direct current to alternating current, which has been accepted to have many improvements and advantages over other forms and types of inverters including the conventional vibrator system shown in figure 1*A*. It is not the intention in the following paragraphs to criticize the present conventional vibrator system, but merely to establish a basis of comparison for what has been considered to be a distinct improvement.

The circuits used for nearly all vibrator applications in the past have been basically similar to the circuit of figure 1*A*. Modifications are found in various methods for starting and driving the vibrating reed. By referring to figure 1*B* it is evident that during the "closed" period of each cycle the line current comprised of I_1 and I_2 continues to increase until the circuit is opened at points *X* and *Y* by the vibrator contacts. Alternate current impulses occur for respective paths of the battery circuit as shown. The general wave shape of the output voltage is acceptable for many applications, however, the fact that the contacts are compelled to break an increasing current at a maximum value proves disastrous for appreciable load currents. The resulting spark produces considerable heat and transfer of contact materials. Extremely high frequency components occur at the "make" and "break" from the resulting spark, to cause objectionable radio disturbance. Suppressors must always be added to avoid such interference. If for any reason, action of the vibratory reed should stop while either set of contacts is closed, the battery or supply-line current would increase to high values only limited by the d-c resistance of the circuit and the protective device, if used. Adequate capacitors are required and are connected either across the output load or across each set of vibrator contacts with correct associated resistance to decrease sparking to a minimum.



A—Conventional vibrator circuit

B—Contact current in circuit of *A*

C—Output voltage from circuit of *A*

Figure 1

New Type Vibrator Circuit

A vibrator-type inverter satisfies the requirements for simplicity, low cost, high efficiency, and very few moving parts. Its serious enemy, as described previously, is the damaging spark during the opening of the contacts. Frequency regulation is excellent. Small size is a desirable feature. To develop a new inverter the decision was made in favor of the vibrator type with the fundamental objective being to reduce the circuit current to zero before allowing the vibrator contacts to open. It was apparent if such a condition could be made possible, the contact life should be very long and result in a most reliable type of inverter. Such was the process of development and the following paragraphs explain the theory followed.

If a reactor *L*, capacitor *C*, and resistor *R*, be connected in series across a source of direct voltage through a switch as shown by the solid lines of figure 2*A*, an approximate sine-wave half-cycle current can be obtained. The extent of continued oscillation will depend upon the damping of the circuit resistance *R*. Assuming the capacitor to be completely discharged when switch 1 is closed, the current will increase to a maximum and reduce to zero as the capacitor becomes fully charged. If switch 1 is opened at point *X* in the current wave I_3 of figure 2*B*, there will be no spark at the switch since the current at that moment is zero and the capacitor will be charged to a potential equal to line voltage. When closing switch 2, capacitor *C* will begin to discharge and force a current I_4 to duplicate the charging current I_3 in all respects except that it will flow in the reverse direction. Again no spark will occur at switch 2 if it is opened at point *Y*. The capacitor and reactor have definite reactance constants, therefore currents I_3 and I_4 individually acquire the same definite resonant frequency. Amplitude of the two waves will be equal providing the

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O. Kiltie is designing engineer, General Electric Company, Fort Wayne, Ind.

The author gratefully acknowledges the assistance of M. A. Edwards, B. D. Bedford, and H. W. Lord of the General Electric Company, Schenectady, N. Y., for their valuable contributions toward this development especially with regard to train lighting, and the work of R. A. Oberlin, General Electric Company, Fort Wayne, Ind., for conducting much of the development testing.

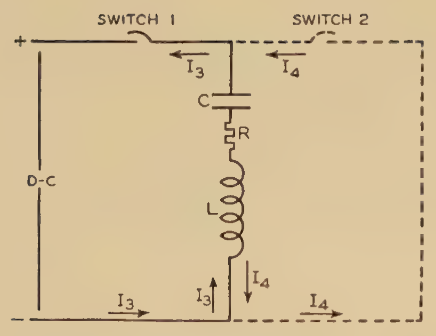

Figure 2A. Circuit to obtain one cycle of charge and discharge alternating current

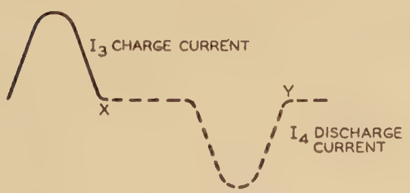

Figure 2B. Charge and discharge current waves

resistances of the two paths are equal. Alternating current can thus be obtained if the switching operations occur alternately and uniformly. For switching purposes the conventional type vibrator may be substituted most ideally if the respective contacts be made to open the circuit corresponding to the points X and Y in the current waves of figure 2*B*. Resistance R represents the load which should be of the proper value to obtain correct damping of the load current. By omitting the reactor the current will increase at a very rapid rate equivalent to a high frequency and the current will decrease, in that same half cycle, at a very slow rate which would be equivalent to a low frequency, so that wave shapes of this type would be of little value for power purposes. A new inverter circuit as shown in figure 3 is thus made possible. The circuit is similar to the charge-discharge circuit of figure 2*A* except that the output transformer has been added to couple the load resistance with the exciting source. Certain type loads may be supplied directly from a single low-reactance transformer excluding the use of a tuning reactor L. Such is possible only where a lagging-power-factor load provides the necessary inductive reactance to reflect in series with the capacitor C to provide the correct resonant frequency. In other applications as described later, for neon-tube purposes, the tuning reactance may be combined in a single output transformer by providing sufficient leakage reactance between the two windings. General applications usually require the inductance be provided as a separate unit and that the output transformer be of the conventional low-reactance type with minimum leakage reactance between windings.

Since the load current can be made to reduce to zero, an ideal time in the cycle is available immediately after each half cycle for the contacts to open the circuit to switch for the alternate half cycle. During the moment of no current flow the contacts may be opened with absolutely no spark or damage whatsoever, and the primary objective of the development has been achieved.

It is essential to choose circuit constants such that the load current will increase to a maximum and decrease to zero during a single closed period of one pair of contacts. To obtain maximum output load watts, it is desirable to open the circuit as soon as possible after zero current has been reached. In other words, load current should flow as much of the time as possible. Uniform resonant frequency of the load current can be easily controlled by holding the reactor and capacitor reactance constants within definite limits. Constant frequency of the vibrator is made available at little extra expense, since the vibratory reed has that inherent characteristic. Since many applications require a specific frequency the frequency of the vibrator must be chosen to agree. The resonant frequency of the load current must then be designed to a value approximately ten per cent higher in order that the contact current is at zero before the contacts open. Absence of current at opening of contacts makes it impossible for destructive sparking to occur. The contacts are required to withstand only mechanical wear and resistance heating.

Line current from the d-c supply consists of charging current only, so the effect is a series of d-c pulsations in exactly the same shape and amplitude as the positive half cycles of the alternating current in the oscillogram of figure 4*A*. Since line current from the battery flows only half the time, a d-c ammeter measurement will be slightly less than half the a-c measurement of current in the capacitor leg.

Perhaps the features and advantages of the new inverter are best proved and most evident by referring to the oscillogram of figure 4*A*, which shows the alternating current I_5 of circuit per figure 3. It consists of both the charge and discharge half-cycle currents in alternate arrangement. The oscillograms of figures 4*A*, 4*B*, and 4*C* were taken with an inverter connected according to figure 3 and connected to a 96-per-cent lagging-power-factor load. The following test data will show actual relative measurements and are true for the conditions of the various oscillograms.

E_1—Line volts, direct current 110
I_6—D-c line current .... 1.4 amperes
E_2—Load volts, alternating current .... 107 (figure 4*B*)
I_8—Load current, alternating .... 1.18 amperes
Load watts 122
I_5—Capacitor current ...... 3.68 amperes (figure 4*A*)
Capacitor C .... 124 microfarads
Reactor L .... 0.0241 henry

Phase relation and comparison may be made of a-c output volts E_2 with capacitor current I_5 by referring to figure 4*C*. It is apparent that wave shapes are quite satisfactory for most purposes. From close inspection of the oscillograms it can be seen exactly where the vibrator contacts close and open.

There are various methods to start the vibrator in motion, the most simple of which is to connect the driver coil of the vibrator directly across the load contacts on the battery side as shown in figure 3. When closing the d-c supply switch an initial current will flow through transformer primary, capacitor, and driver coil. Even though this current is small it establishes a directional flux to start operation of the vibratory reed in the usual manner. During the initial swing of the reed the corresponding contacts close and allow for the first half cycle of charging component of the load current. Simultaneously, the driver coil becomes short-circuited to remove the magnetic pull upon the reed, which allows the reed to swing back across the center position to close the other pair of vibrator

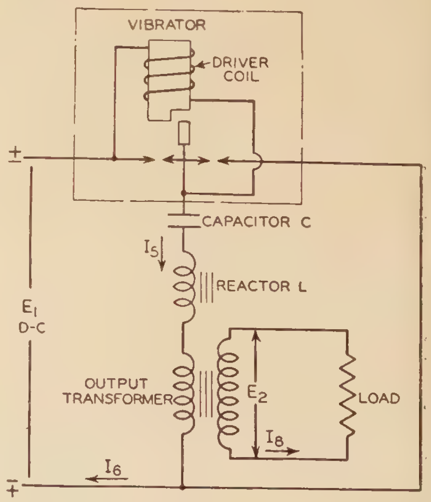

Figure 3. New type of d-c to a-c vibrator inverter

contacts. During this period the discharge half cycle occurs. Since the short circuit has been removed from the driver coil, the reed is again pulled in the opposite direction to repeat the continuous cycle. The natural frequency of the reed determines the a-c frequency.

This development has created new requirements for capacitors. The volt-ampere output depends directly upon the value of capacity, so for appreciable loads from low direct voltages especially, the number of microfarads reaches a large figure. The a-c electrolytic type capacitor has proved most suitable for such requirements, chiefly because of its small size and low cost. Power factor and losses should be low. Inductive effects in the capacitor and in the lead connections between the terminals and foil create a surge impedance which may reject a capacitor satisfactory in other respects.

The a-c output can be synchronized with an isolated a-c power source by providing the driver coil of the vibrator with a suitable low voltage obtained directly from the synchronized voltage.

An important feature is that which allows the d-c supply current to reduce to zero if the vibratory reed should stop in any position of its normal operating range while the d-c line switch remains closed. Since the capacitor becomes charged and remains charged, no current can flow. The battery or d-c circuit is opened if the discharge contacts remain closed.

From this development it appears the new inverter will be ideal for many specific applications. At the present time much hope is held for it to enable the use of standard 110-volt a-c television receivers in d-c districts, its chief advantage being in constant frequency and lack of disturbing interference. Radio receivers on police cars are required to operate almost continuously. The plate-supply direct voltage can be supplied from a vibrator of this type with considerable assurance of reliable operation.

Application for Neon Signs

The original purpose of this development was to find a new cheap method to supply suitable high voltage for neon signs on automotive vehicles. For such purposes the inverter must operate on any condition from short-circuit to open-circuit loads. A circuit the same as figure 3 may be used except that the output transformer requires sufficient leakage reactance between windings to hold the tuning reactance within reasonably close limits to prevent contact sparking for the various load conditions. An inverter suitable for most neon sign applications for 6.0-volt d-c service supplies 7,500 volts open circuit which is suitable for ten feet of nine-millimeter-diameter red neon tubing. Battery drain is almost constant at 3.5 amperes for any load condition. An electrolytic capacitor of 6,500 microfarads is necessary for this purpose. Wave shapes are so favorable that smoothness and appearance of the tubing while operating is comparable with that from any commercial a-c supply.

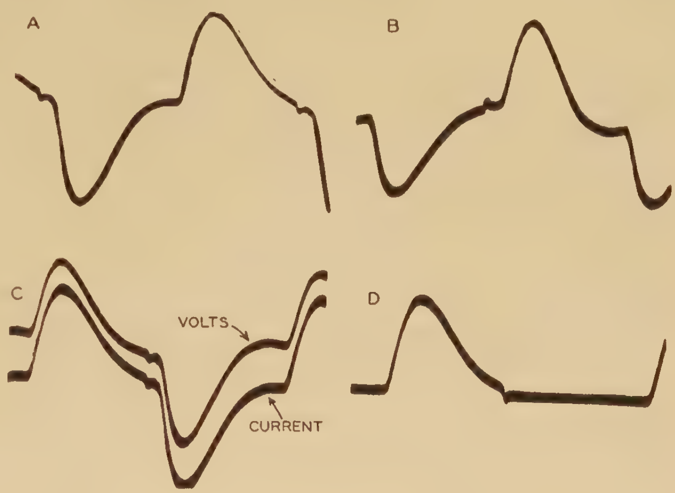

Figure 4. Oscillograms of inverter current and voltage of figure 3

A—Alternating current I_6

B—Output alternating voltage E_2

C—Relation of current I_6 and output voltage E_2

D—D-c line current I_6

Application to Fluorescent Mazda Lighting on Railway Cars

The problem of supplying suitable a-c power to a group of the new fluorescent Mazda lamps from 32- or 64-volt batteries seems to be very well satisfied by this type of inverter. An efficiency of 75 per cent is maintained throughout the normal variation of the battery voltage. Best operation is obtained with a load power factor near unity although variations, either leading or lagging, may be tolerated.

Several railway cars[1,2] have now been equipped with fluorescent lights and vibrator inverters of this type.[3] With no changes necessary to the batteries and generators of existing equipment in service, it is possible to increase the average illumination on the reading level from approximately three foot-candles with tungsten lamps to approximately eleven foot-candles with fluorescent lamps. The losses of the inverter and lamp ballast auxiliaries have been considered in this comparison.

The constant frequency of the inverter power supply becomes a valuable feature since the lamp auxiliary is of the reactance type. Even with battery voltage variations from 28 to 43 volts the vibrator has been made to hold almost constant amplitude of the vibratory reed and to provide almost a constant frequency of 60 cycles. Therefore, with a constant frequency of the power supply the voltage may be allowed to vary to some extent without causing damage to the auxiliaries or to the fluorescent lamps. It then makes it possible to eliminate the lamp regulator which has been necessary for tungsten lamps on railway cars.

Present rated outputs from 32-volt sources have not yet much exceeded 250 watts, so for loads of 1,000 and 1,500 watts, panels of four sections and six sections respectively are used. Each 250-watt section is connected to a group of from 12 to 16 lamps as required. Progress of development for the actual installations in service has been conservative on the safe side. It is evident that the present output can be increased, although it is believed that standardization of ratings may establish the 250-watt size as close to the preferred rating.

This entire development is so new and recent that further research and development will naturally bring many improvements.

References

1. *Railway Electrical Engineer*, March 1939, page 41.

2. *Railway Electrical Engineer*, October 1938, page 212.

3. *General Electric Review*, January 1939, page 32.

Discussion

B. D. Bedford (General Electric Company, Schenectady, N. Y.): Mr. Kiltie's paper is of great value in that it introduces a vibrating-switch inverter employing an

Variable-Voltage Equipment for Rotary Drilling Rigs

E. H. LAMBERGER
ASSOCIATE AIEE

THE PURPOSE of this paper is to tell why variable-voltage equipment should be considered for oil-well drilling rigs, to explain the operating characteristics of a typical equipment, and to compare the over-all performance with that of an equivalent mechanical drive.

The variable-voltage drilling rig is associated with internal-combustion engines. Steam turbines have been suggested for prime movers, but have not yet been used. A-c motors can be used to advantage, and have been proposed, but to our knowledge never actually used.

Let us review briefly some of the disadvantages of steam equipment as compared to the internal-combustion engine. A safe and adequate water supply for steam boilers is sometimes difficult and expensive to obtain. The water supply for cooling internal-combustion engines is, comparatively, a small amount. Steam boilers are bulky and heavy units. There are usually not less than three per rig, each weighing approximately 30,000 pounds or as much as the two large-capacity Diesel engines used on a comparable heavy-duty mechanical drilling rig. The boilers are also much bulkier than the engines. Inspection and maintenance is a more serious item with boilers than with internal combustion engines. Steam offers the possibility of boiler explosion which represents a hazard to life and property. The open fire under the boiler presents a real hazard in case of a gassing well. When gas is not available, as in the case of "wildcatting," the transportation of other fuels in quantities required for steam generation entails considerable expense. Assuming liquid fuel, the quantity required for internal combustion engines will be considerably less than that for boilers.

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The development of reliable high-speed internal-combustion engines of adequate rating, brought a real competitor of steam as a source of power for drilling oil wells. While steam rigs still predominate by a wide margin, the internal-combustion-engine drive is being used in increasing numbers. Improvements in steam equipment such as the use of higher steam pressures (500 to 800 pounds per square inch) and superheat, will undoubtedly be matched by improvements in internal-combustion-engine equipments such as the development of larger-capacity and higher-speed engines. Variable-voltage transmission with its many advantages will help in further increasing the use of the internal combustion engine.

Difficulties Encountered With a Mechanical Transmission

As the internal-combustion engine cannot pick up any appreciable load from standstill, a clutch must be provided. This clutch must slip while the load is being accelerated to a speed corresponding to the engine speed, and at the same time transmit a torque as required by the load. This means clutch wear. The manipulation of the clutch results in engine stalling or near stalling, sudden changes in engine speed, and shock loads on the engine and mechanical transmission. Such factors mean high maintenance of the engines and of the entire mechanical transmission. Also, it is practically impossible to pick up a heavy load with the smoothness desirable when doing a fishing job. The mechanical transmission is inflexible as to arrangement because the engines must be close to the draw works and the mud pump.

What Is Meant by a Variable-Voltage Equipment

Before considering the advantages of a variable-voltage drilling equipment let us outline briefly what such an equipment consists of. Such an equipment consists of d-c generators a portion of whose fields are supplied by separate excitation, and whose voltages are varied and reversed by controlling their fields; motors with shunt fields separately excited, so their direction of rotation and speed are changed as the polarity and value of the generator terminal voltages are changed; constant voltage exciters to provide for separate excitation of generators and motors, and a source of auxiliary power;

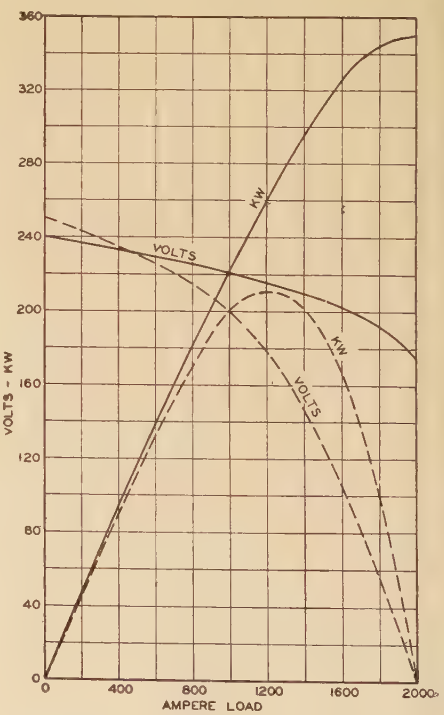

Figure 1. Generator characteristics

Solid curves—With separately excited and self-excited shunt fields

Dashed curves—With separately excited and self-excited shunt fields and also series differential field

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improved method of commutation. This improvement makes this type inverter capable of handling much larger loads, with reduced contact wear. The new design greatly expands the number of applications in which vibrating-switch inverters may be used.

Practically all small independent electric power systems, such as those found on automobiles, railway cars, airplanes, small boats, and isolated farms, obtain continuity of service by storing electric energy in batteries. At present, the manufacturer must design and the consumer must buy many special lamps, motors, and other appliances for operation on these low-voltage d-c circuits. The vibrating-switch inverter will have an important place in the electrical field, for it is now practical to convert the battery energy of these independent systems to alternating-current so that standard a-c apparatus may be used.

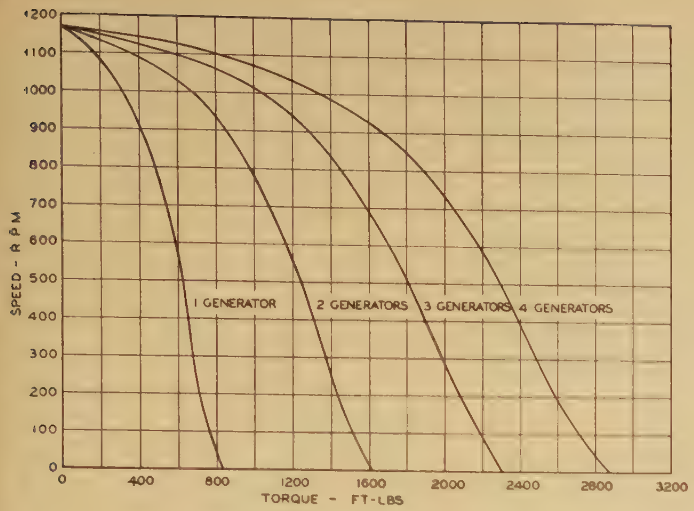
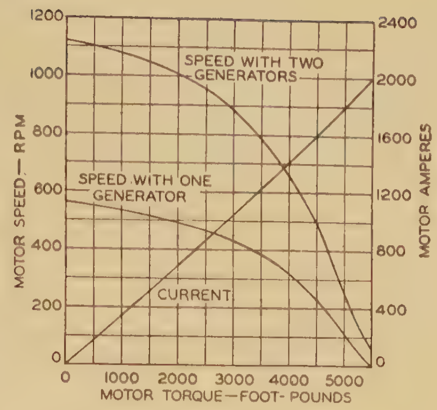


Figure 3 (left). Motor speed-torque characteristic with generators in parallel

Figure 4 (right). Motor speed-torque characteristic with generators in series



a control equipment which gives full control of power application to all main motors for drilling or hoisting operations from the driller's position.

The generators as here used are more than simply variable-voltage machines. In addition, they have a shape of voltage curve which droops to zero at some predetermined current value. Such a curve establishes two desirable limits:

1. The peak generator output and consequently the peak demand on the engine can be limited to the maximum desirable output of the engine. Once established the protection to the engine is automatic, regardless of pump, table, or hook load. The electric motors can even be stalled without danger of stalling or even slowing down the engines.

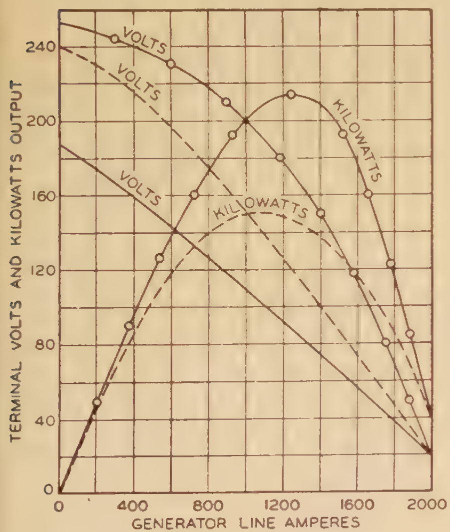


Figure 2. Generator voltage and kilowatt characteristics

Circles—Three-field generator with series differential field

Solid curve—Three-field generator with self-excitation eliminated

Dashed curves—Two-field generator with series differential field

2. The maximum current that can be circulated when a motor is stalled can be limited to that value which is considered a safe maximum from the standpoint of both the mechanical and electrical equipment. Such a limitation is particularly desirable for mud-pump and table drives.

How these generator characteristics are obtained will be discussed in detail later in this paper.

Separate shunt excitation of the motors provides two principal advantages. (1) The motors are reversed as the applied armature voltage is reversed. Motor reversing is therefore accomplished by means of only small generator-field-circuit contactors. With series or compound fields, large main-circuit contactors would be required. (2) The use of a separately excited field assures that the torque exerted by the motor will be always proportional to the armature current. This is important where high momentary torques are required, as when pulling on a stuck pipe.

The exciters, or auxiliary generators, are constant-voltage machines. They are suitable as exciters for the fields of the generators and motors, and as a source of auxiliary power for lighting, shale-shaker motor, raw-water motor, engine-cooling-tower circulating-pump motor, and any other auxiliary load.

The control is relatively simple. Since motor speed control and motor reversing are accomplished by the manipulation of only small generator field currents, the necessary circuits can be handled directly on a drum controller. It is therefore easy and economical to provide a large number of speed points. Means are provided for transferring available generator capacity to any motor circuit in case of emergency. Derrick-floor control units, such as the master controllers, drill-hoist selector switch, and emergency stop push button, are of the oil-immersed or explosion-proof type. Master controllers provide for 20 points of speed control and are operated from the driller's position.

Generator Characteristics

Let us consider how the generator characteristics referred to above are obtained.

Figure 1 illustrates the voltage and kilowatt characteristics of a generator equipped with only shunt fields, including both self- and separate excitation, and the same generator equipped with self- and separately excited shunt fields and also differential series fields. It is apparent that the machine with only shunt fields has a power demand characteristic which would be unsuited to internal-combustion-engine drive on a drilling rig. The demand on the engine with such a generator characteristic increases approximately in proportion to the current or motor torque required. It would require careful attention of the operator to avoid overloading and stalling of the engine. Such close attention is not desirable.

The curves for the generator arranged with shunt fields and differential series fields indicate that the maximum demand on the engine can be limited. The demand on the engine actually decreases as the armature current increases beyond that value corresponding to the peak generator kilowatts. This means that the engine is actually working more easily when excessive motor torque or hook pull is being exerted than when normal torque or pull is required.

Either of these generators could be of the variable-voltage type. In the first case the operator must give attention to engine loading, while in the other case the engine is automatically protected against overloading.

A drooping generator characteristic can be obtained by using only a sepa-

rately excited shunt field and a differential field, referred to as a two-field design, or by using a separately excited shunt field, a self-excited shunt field, and a differential series field, referred to as a three-field design. The three-field design has the advantages that for a given frame size a higher no-load voltage, a greater continuous kilowatt rating, and a greater peak kilowatt output are obtainable than are possible with a two-field design. These results are due to the following reasons.

In either case, at the maximum desired armature current the differential series field must be approximately equal in strength to the separately excited shunt field. If the shunt excitation is made up entirely of separate excitation, the series field will occupy a greater percentage of the field space than it would if the separate excitation were only one-half of the total shunt excitation. Therefore the space for shunt, or positive excitation is less in the two-field generator than in the three-field machine. Also the self-excited shunt field provides an automatic increase in excitation with increased voltage, within the limits of the saturation curve of the machine.

Figure 2 illustrates typical voltage and kilowatt output characteristics of the two different field windings on a given frame size of generator. The no-load voltage of the two-field generator is 241 volts compared to 253 volts for the three-field machine. The voltage of the two-field machine drops quite rapidly with increase of load from no load, while it is relatively well sustained in case of the three-field design. This means higher operating speeds for light loads. Assuming that each machine is to rate 1,000 amperes, it will be noted that the voltages at this current for the two- and three-field generators are 150 volts and 200 volts respectively. Therefore the rating of these machines would be 150 kw and 200 kw respectively. It will be noted further that the peak output of the two-field machine is very little greater than the rated value, while the three-field machine gives a peak output seven per cent higher than its rating. Therefore, the assumed frame with three fields can transmit a peak engine horsepower corresponding to a generator output of 214 kw, while the two-field machine can transmit an engine horsepower corresponding to a peak generator output of only 152 kw.

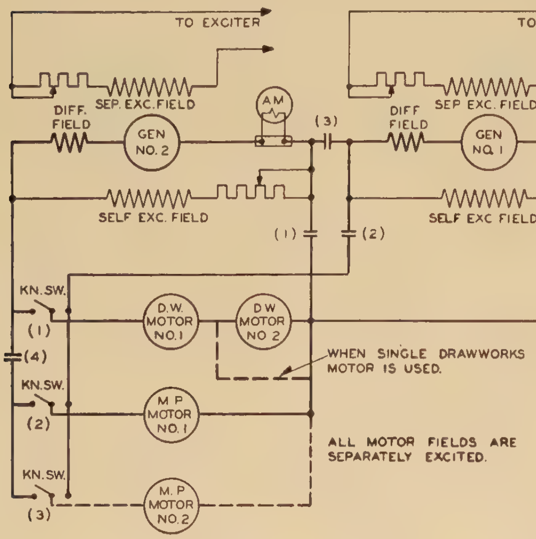


Figure 5 (left). Schematic wiring diagram

Two generators arranged for series operation during hoisting

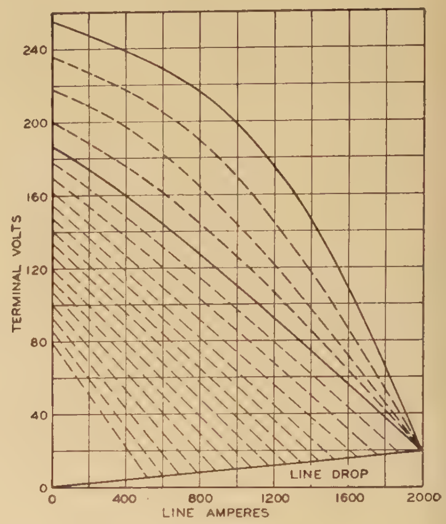


Figure 6 (right). Voltage characteristic of typical 200-kw generator illustrating voltage curves to give 20 points of motor speed control

Types of Equipment

The equipment may be "full electric" or "semielectric." With a full-electric equipment the draw works, table, and mud pump are all driven electrically. The table may be driven by the drawworks motor through the draw works, or by a separate table motor. With a semielectric equipment the mud pump is driven mechanically.

Generators may be connected in series or in parallel. Figure 3 illustrates the speed-torque characteristics of a motor operating on one, two, three, or four generators in parallel. It is evident that the loss of a generator reduces almost proportionately the motor torque available. This is a disadvantage of this system. Paralleled generators have the advantage however that standard-voltage machines may be used, regardless of the number.

Figure 4 illustrates the speed-torque characteristic of a motor operating on one or two generators in series. It is evident that the loss of one generator means only a negligible reduction in maximum motor torque. There is however a proportionate reduction in motor speed. There is a practical limit to the number of generators which can be used in series. From the standpoint of safety and from the standpoint of standard industrial insulation limits the maximum generator voltage should not exceed 600 or possibly 750 volts. It is evident then that if a large number of generators are used the voltage rating will be low with consequently high ampere rating. In extreme cases this results in expensive generators.

Advantages of Variable-Voltage Electrical Transmission

In view of the above characteristics of a variable-voltage d-c equipment for

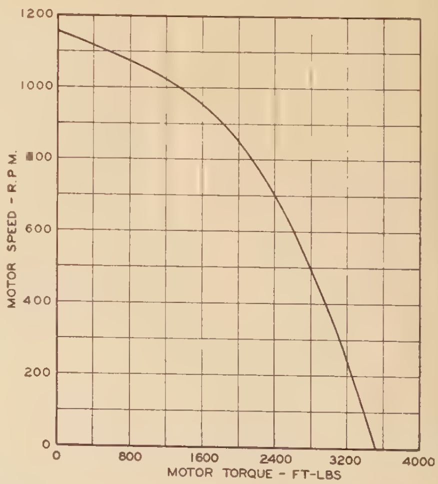


Figure 7. Speed-torque characteristics of 300-horsepower mud-pump motor operating on 250-kw generator

Table I. Data on Weights, Speed Ratios, Mechanical Efficiencies, and Times Allowed for Making and Breaking Joints

Maximum depth of hole (feet)	6,480
Weight of traveling block, hook, and elevators (pounds)	15,000
Weight of 6,300 feet of $6^5/_8$-inch 31.9-pounds-per-foot drill pipe (pounds)	200,000
Weight of reamers, drill collars, and bit (pounds)	15,000
Total effective weight of string (pounds)	230,000
Number of lines used	6 or 8*
Governed engine speed—either drive (rpm)	600
Speed ratios—electric drive:	
Drilling gear—internal	3.2:1
Drilling gear output shaft to draw-works jack shaft	1:1
Over-all—motor shaft to draw-works drum shaft:	
High-high	2.85:1
Low-high	4.74:1
High-low	10.50:1
Low-low	17.50:1
Speed ratios—mechanical drive:	
Engine through reverse gear to draw-works jack shaft	2.8:1
Over-all—engine to draw-works drum shaft:	
High-high	2.49:1
Low-high	4.14:1
High-low	9.18:1
Low-high	15.3:1
Mechanical efficiencies (per cent):	
Electric drive:	
From engine flywheel to generator pulley	95
From draw-works motor shaft to hook	74
Mechanical drive:	
From engine flywheel to reverse gear	92.7
Through reverse gear to hook	73.3
Over-all efficiencies from engine flywheel to hook, at maximum output:	
Electric drive	56.8
Mechanical drive	67.8
Effective drum diameter—second layer $1^1/_8$-inch line (inches)	29
Coming out, either drive, six or eight lines:	
Seconds allowed to break joint, set stand aside, and drop hook (per stand)	35
Going in, either drive, six or eight lines:	
Seconds allowed to pick up stand, make joint, and drop string (per stand)	50

* Assume buoyancy counteracted by friction during hoisting.

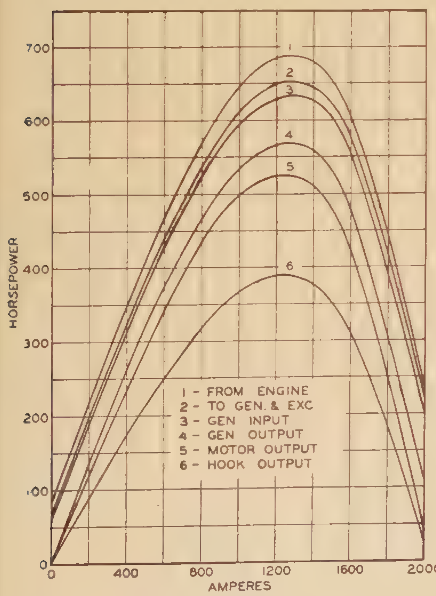


Figure 8. Power absorption between engines and hook with electric transmission

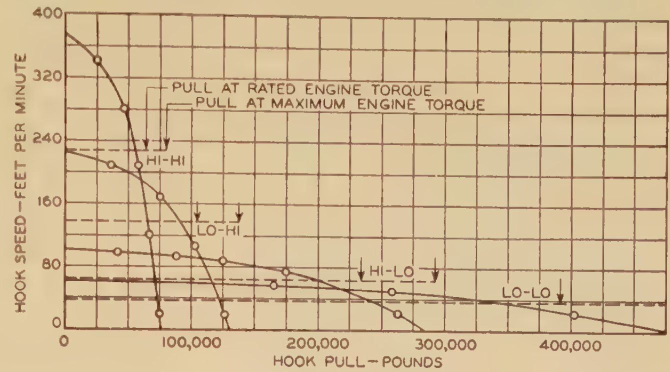
oil-well drilling, let us consider the advantages offered by this type of power transmission as compared to a mechanical transmission.

1. Engine-clutch manipulation in connection with load pickup is eliminated. The clutches are used only when starting up the generator set, therefore delays and expense due to clutch maintenance are negligible. Shocks to engine and mechanical equipment incident to clutch manipulation when picking up loads are eliminated, and consequently maintenance of mechanical equipment and delays caused thereby are reduced.

Figure 9. Hook speed versus hook pulls for various draw-works combinations using eight lines

Solid curves—Electrical drive

Dashed curves—Mechanical drive



2. The engine cannot be overloaded or stalled. This eliminates delays in operation. The engine operates at constant speed regardless of load, a condition much easier on the engine than when speeds are varied widely and suddenly.

3. Loads are picked up smoothly. The inherent characteristics of the electrical equipment, including the control, prevent shock loads on the engine or the mechanical equipment.

4. A wide range of motor speeds and torques is available. Voltages at light loads, and consequently operating speeds with such loads, are 15 to 25 per cent above rated speeds; full-load torques may be handled at many speeds ranging from zero to full speed; torques ranging from 40 per cent to 200 per cent of full-load torque may be exerted at zero speed; the maximum torque to be exerted at zero speed can be predetermined.

5. Operating records are easily obtained. Engine performance may be checked by measuring generator output; energy consumption for various operations may be determined; charts showing changes in operating conditions may be obtained.

6. Equipment may be located to best advantage. The power plant and mud pit may be placed at any convenient location.

7. Flexibility as to prime movers and total rig capacity are provided. Engines of the Diesel, gas, or gasoline type or a-c motors may be used as prime movers; one or a few large engines, or many small engines may be used; two separate equipments may be used on one rig to double the power available.

8. Loss of an engine does not reduce the maximum hook pull available when generators are connected in series.

A Typical Equipment

A typical full-electric equipment with two generators arranged for operating in series during hoisting would consist of the following apparatus:

1. One complete generator unit consisting of the following:

(*a*). One 250-kw 200-volt 1,200-rpm generator

(*b*). One 200-kw 200-volt 1,200-rpm generator

(*c*). Two 20-kw 115-volt 1,200-rpm exciters

(*d*). Equipment assembled and wired on rigid skid-type bedplate

2. One 200/400-horsepower 200/400-volt 450/900-rpm draw-works motor

3. One 300-horsepower 200-volt 900-rpm mud-pump motor

4. One 200-horsepower 200-volt 900-rpm auxiliary mud-pump motor

Note: All ratings are continuous based on 40 degrees centigrade rise. This allows for overloads and high ambient temperatures encountered in drilling oil wells. Forced ventilation of motors is used so that (1) motor ventilation will not vary with motor speed, thus assuring full ventilation with overloads, and (2) to make it possible to provide safe air to the motor in case of gaseous atmosphere.

5. One complete variable-voltage control equipment which would include the following items:

(*a*). One main control cabinet containing contactors, relays, knife switches, exciter meters and rheostats, etc.

(*b*). One derrick-floor resistor rack, containing generator field resistors, and with two 20-point reversing oil-immersed master controllers mounted thereon

(*c*). One draw-works post control mechanism, with two wheels arranged so that generators may be controlled independently during drilling, or simultaneously during hoisting

(*d*). One oil-immersed selector switch by means of which the circuits are set up for drilling or for hoisting

(*e*). One explosion-proof emergency stop push button

(*f*). One weatherproof meter cabinet with an ammeter for each generator circuit

Typical Main Circuit Diagram

Figure 5 shows a typical main circuit diagram for a two-generator full-electric equipment arranged for inde-

pendent use of generators during drilling and series-connected generators during hoisting.

Performance of Typical Equipment

During drilling the 200-kw generator supplies power to the draw-works motor for table drive, or to the separate table motor if used. The 250-kw generator supplies power to the 300-horsepower mud-pump motor. The voltage characteristic of the 250-kw generator is similar to that shown by figure 6 for the 200-kw generator except that for this machine the curve drops to 20 volts at approximately 2,500 amperes, and produces rated voltage at 1,250 amperes. This figure also illustrates the speed control provided by the 20-point controllers. The speed-torque curve of the mud-pump motor operating on the 250-kw generator is illustrated by figure 7. It may be pointed out here that the engine capacity need not be sufficient to carry a total generator output of 450 kw. Let us assume two 350-horsepower engines are used. The two engines drive the generator set and are connected by a coupling between the generators. They therefore divide their output between the generators as required. During drilling the power demand for table drive is usually considerably less than 200 kw, and therefore adequate engine capacity is delivered to the 250-kw generator so the mud-pump motor can operate at full capacity.

During hoisting the characteristic of the 250-kw generator is automatically changed to match that of the 200-kw generator, so that the combined total rated output of the two generators is 400 kw. The 400-horsepower draw-works motor takes the full output of the two generators during hoisting. While the motor is overloaded at times, this is permissible as this motor was previously only partially loaded and because the effective value of the load may still be within a safe value from the standpoint of final motor temperature since the hoisting job is done in a relatively short time.

Transmission Efficiencies

Figure 8 illustrates distribution of engine power during hoisting, from the engine flywheel to the hook, exclusive of that power required for auxiliary circuits. Curve 1 of this figure illustrates the maximum demand which can be made upon the engine for any indicated ampere load on the two generators in series. The maximum possible demand is 687 horsepower, which would be the required output of the two engines combined. This peak power demand occurs at approximately 1,300 amperes. The power demand decreases for current values greater or less than this value. It is therefore evident that as the demand for hook pull becomes excessive, the load on the engine actually decreases, thereby eliminating any possibility of stalling the engine.

The difference between curves 1 and 2 represents the power absorbed in the mechanical transmission between the engine and the generator set pulleys. The difference between curves 2 and 3 represents the power required for electrical excitation and control, and for the necessary motor blowers. The difference between curves 3 and 4 represents the losses in the generators, and the difference between curves 4 and 5 represents the losses in the cable and the draw-works motor.

Curve 5 indicates the power available at the motor shaft, with a peak value of 526 horsepower corresponding to the 687-horsepower engine output value. This represents a transmission efficiency from engine flywheel to motor shaft of 76.8 per cent. Curve 6 indicates the power available at the hook. With 687 horsepower demanded from the engine, the output at the hook is 390 horsepower. The over-all efficiency from engine to hook is therefore 56.8 per cent.

Similar calculations for the mechanical transmission result in an output at the hook of 466 horsepower, with an engine output of 687 horsepower. This

Figure 12. Time for coming out of and going into 4,680-foot hole using six lines

Solid curves—Electrical drive

Dashed curves—Mechanical drive

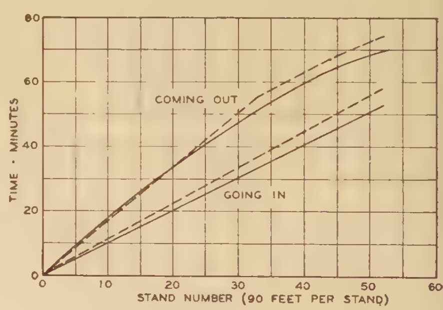


Figure 10. Hook speed versus hook pulls for various draw-works combinations using six lines

Solid curves—Electrical drive

Dashed curves—Mechanical drive

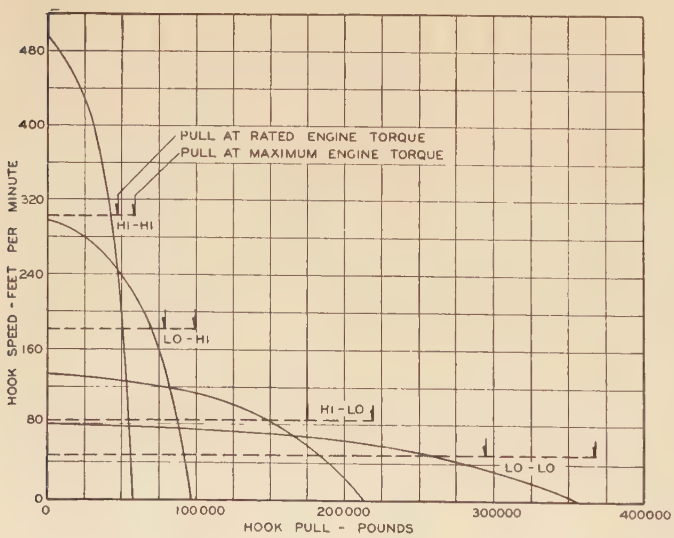
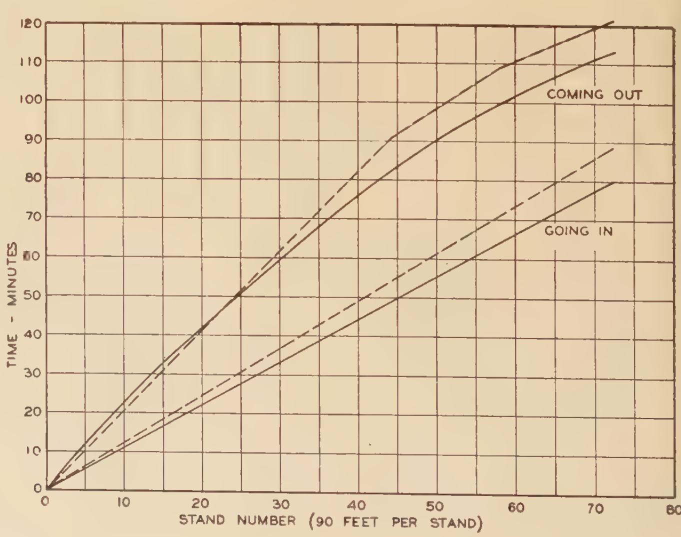


Figure 11 (below). Time for coming out of and going into 6,480-foot hole using eight lines

Solid curves—Electrical drive

Dashed curves—Mechanical drive



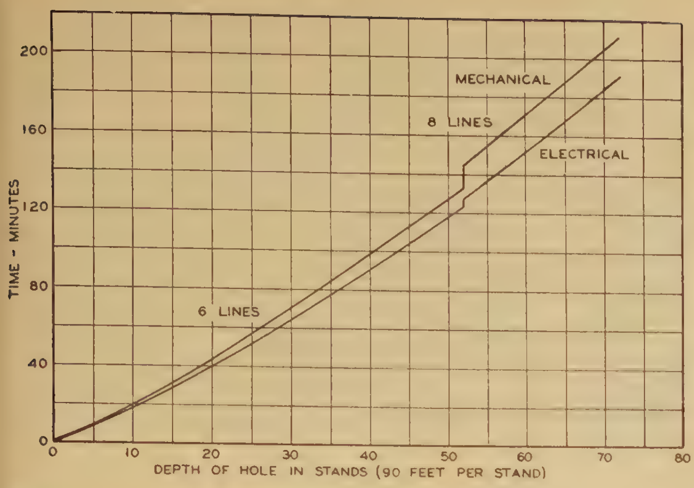


Figure 13. Time required for making round trip for any depth hole up to 6,480 feet, 72 stands, using six lines to 52 stands, eight lines 53 to 72 stands

Identical engines used with both drives

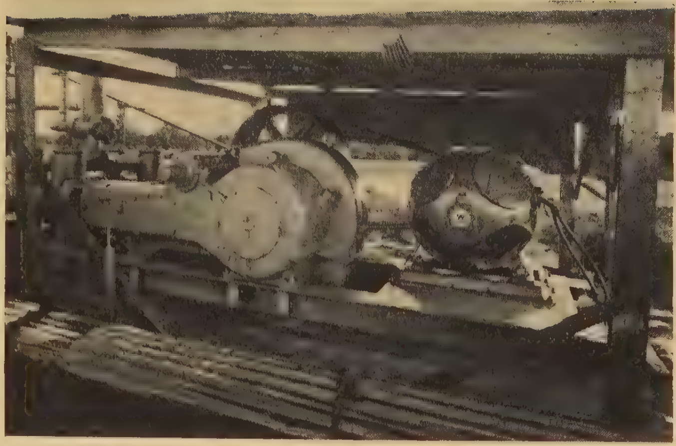


Figure 14. A 200-horsepower mud-pump motor

Figure 15. A 400-horsepower draw-works motor

Figure 16. A 75-horsepower mill-type table motor

represents an over-all efficiency of 67.8 per cent for the mechanical transmission as compared to 56.8 per cent for the electric. The efficiencies used for the various mechanical portions of the drives between the engine and the hook are given in table I.

Comparative Performance When Hoisting

Figure 9 illustrates the motor characteristics with two generators, of figure 4 converted into hook pull and hook speed, with a four-speed draw works and with eight lines on the blocks. Figure 10 illustrates the same characteristics with six lines on the blocks. Table I gives the data used for these conversions.

Figures 9 and 10 also show the hook pull-speed characteristics possible with the same engines but with mechanical transmission. The same draw-works unit is used for both drives.

The rated horsepower available to either drive is 650 horsepower. It is assumed that the engines have a maximum overload capacity of 25 per cent. The electric drive uses some of this margin when developing its peak output when hoisting, while the mechanical drive uses a corresponding portion when accelerating loads at the time draw-works combinations are changed. It will be noted that the maximum hook pull available for each draw-works speed combination is approximately the same for both drives. The equipments are therefore on a comparable basis from the standpoint of over-all speed ratios and use of engine power.

For each draw-works combination the hook speed with electric transmission becomes considerably higher than is possible with the mechanical transmission. This is because the electric motors increase in speed as the load decreases. No such increase in speed is possible with mechanical transmission because the engine is held to a definite maximum desirable speed by the governor. At heavy pulls the hook speed with mechanical transmission is higher than with the electric transmission. It should be noted, however, that the increase in hook speed with reduction in hook load is relatively rapid with the electric transmission. It may also be observed from these curves that the electric drive follows more closely the curve of constant horsepower than does the mechanical transmission.

An attempt has been made to calculate the hoisting performance of each of these equipments. The depth of hole, the weight of equipment, and other pertinent data on which these calculations were based are given in table I.

Figure 11 shows the time required for coming out and going into a 6,480-foot hole, for both equipments with eight lines on the blocks. The curves for coming out illustrate the higher speed of the mechanical equipment at very heavy loads, and the higher speeds of the electric drive at lighter loads. Thus, at about the 24th stand the accumulated time for the mechanical rig becomes greater than for the electric rig. When going into the hole the time is always less with the electric drive. This is due to the higher free-hook speed with this drive.

The total saving in round trip time with the electric rig as indicated by figure 11 is approximately 18 minutes. This is a saving of 8.6 per cent of the time required with the mechanical transmission, which is approximately 210 minutes.

Figure 12 shows comparative performance of the two transmissions with six lines on the blocks when coming out of and going into a hole 4,680 feet (52 stands) deep. The saving in time per round trip with the electric transmission

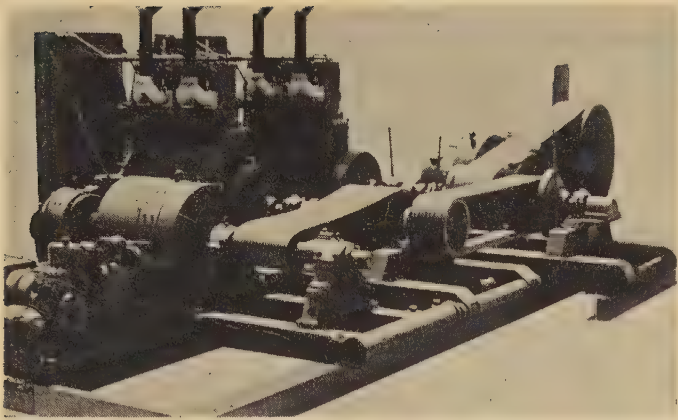


Figure 17. Semielectric-rig power unit

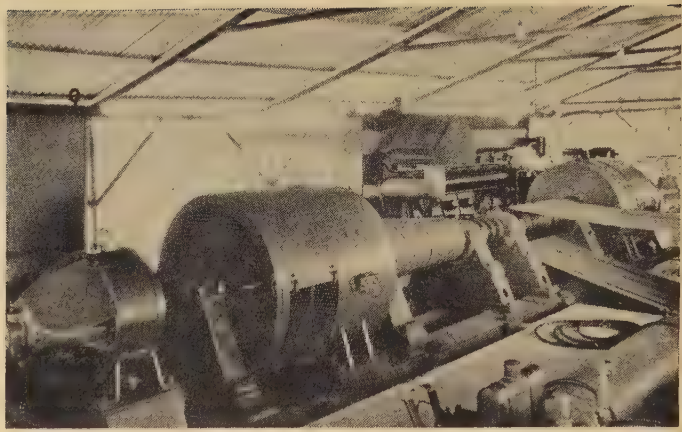


Figure 18. Full-electric-rig power unit with belted generators

is 9.5 minutes or seven per cent of the 132 minutes required with the mechanical drive.

Figure 13 shows the time required to make a round trip to any indicated depth for each type of transmission. It is assumed six lines will be used until a depth of 52 stands is reached after which eight lines will be used. From this curve can be calculated the total comparative time for making all round trips during the drilling of a well. If we assume an average bit life of 90 feet of hole, after drilling to 450 feet, the number of round trips to drill to 6,480 feet would be 66. The time for making each round trip to renew the bit can be taken from figure 13.

The total time required with a mechanical transmission would be 114 hours, as compared to 103 hours with the electric drive. This means a total saving of 11 hours or 9.6 per cent with the electric transmission as compared to the mechanical transmission.

This saving in time takes into account only the comparative speed-pull characteristics of the equipments and does not include savings in time that are realized with the electric transmission as a result of easier and more flexible control manipulation by the operator, elimination of delays incident to overloading or stalling the engine, and eliminating of delays incident to failure or maintenance of the mechanical transmission as a result of shock loads occuring therewith. The savings shown are obtained in spite of the lower overall efficiency of the electric drive. They are due to the higher speeds at light loads and to the inherent characteristic of the electric transmission which more closely follows the curve of constant horsepower.

Summary

Compared to a mechanical drive, the d-c variable-voltage transmission has several important advantages. These are:

1. Loads may be picked up smoothly and handled smoothly over a wide range of controlled speeds.

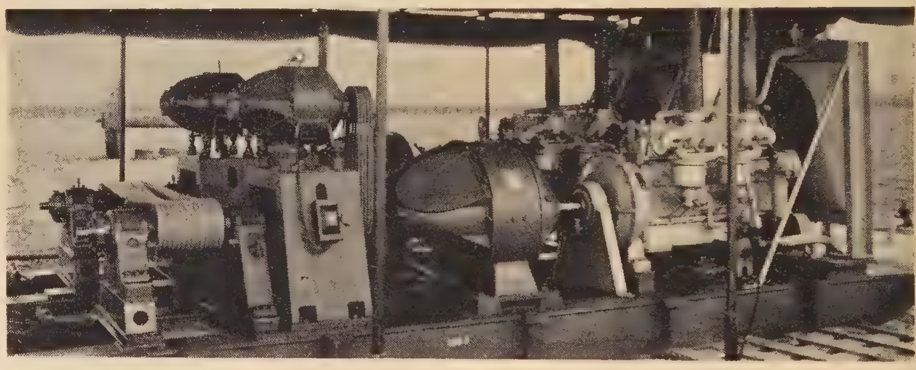


Figure 19 (above). Power unit with two cross-connected direct-connected generators

Figure 20. Four close-coupled engine-generator sets mounted on trailer

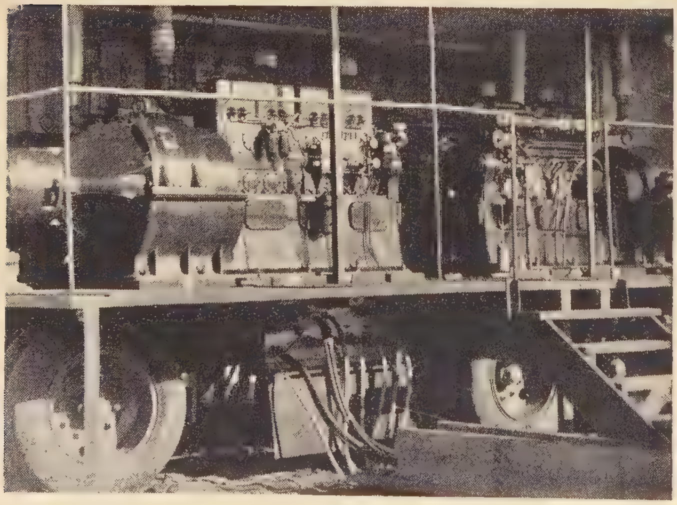


Figure 21 (below). Twelve-generator power plant made up of two six-generator equipments

2. Flexibility as to: location of equipment; number, type, and capacity of prime movers; and combining of two equipments.

3. Lower maintenance of power plant and transmission due to elimination of abuses incident to clutch manipulation.

4. More continuous drilling due to elimination of delays incident to clutch manipulation, to inherent operating characteristics, and to less time out for repairs.

In view of such advantages drilling costs should be less.

Discussion

T. M. Keiller, H. C. Le Vois (nonmember), and **E. L. Robinson** (nonmember; all of Gulf States Utilities Company, Beaumont, Tex.): In the Gulf Coast region, electricity has been extensively used for all the various power requirements of drilling, oil production, transportation, and refining.

The wildcat or exploration well is often quite a distance from sources of electrical energy, but we have numerous instances of temporary power lines built to locations that, in some cases, prove producing fields. Humble Oil and Refining Company has just built $7^1/_2$ miles of 33-kv line across coastal marsh and running 1,600 feet out into the Gulf of Mexico. On this rig, wound-rotor motors are used, but the advantages of variable-voltage control could be realized by the use of an a-c motor generator set.

This system, more nearly approximating the steam rig in drilling characteristics, has in addition an advantage over straight a-c motors in the possible use of comparatively high-voltage synchronous motors with high power factor and attendant reduction in voltage regulation, often a factor in service to remote oil fields.

Should central-station service not be available on an economic basis, considering the possible duration of the requirements, it may be desirable to install a central power plant, distributing energy to several rigs, in which case the a-c motor generator set would be desirable.

From the point of view of the supplier of energy, the definite maximum demand, the absence of severe peaks, and the high power factor attainable, makes the a-c motor generator set with variable-voltage equipment a more desirable load than a straight a-c rig.

Another decided advantage that can be gained with the use of variable-voltage control with purchased electric power through the use of motor generator set is a saving in weight and space over Diesel electric. A large amount of activity along the Texas and Louisiana Gulf Coast is being carried on in salt marshes, open salt-water bays, and in the open Gulf, where the problem of adequate foundation is of prime consideration and great expense. The use of purchased electric power would permit lighter foundations, due to less equipment weight, therefore, greater foundation economy.

In addition, practically all fresh-water requirements would be eliminated. The cooling systems of engines used for generator drives require several barrels of make-up water per day. The hauling of fresh water is an expensive item and can be practically eliminated.

A safety feature in deep drilling is that variable-voltage control prohibits the placing of excessive strain on lines and derrick, thereby eliminating the possibility of pulling in the derrick.

Another advantage is that, if space and weight saving is desired but variable voltage is required on the draw works, a motor-generator set of sufficient capacity could be used for the draw-works motor only. The synchronous motor on the motor generator set could have an excitation range of sufficient capacity to correct power factor for a-c motors on the mud pumps. This would sacrifice the advantage of using variable-voltage control on the mud-pump motors, which provides against excessive duty on the pumps when washing a bridge-in well or stuck drill stem.

The driller would profit either in the purchase of power or generation in the central station from the reduction in demand, increase in power factor, and higher load factor possible. With more than one rig, diversity of peak demand would reduce the aggregate demand on the power source.

Once drilling crews become accustomed to the use of electric power rigs, they appreciate the ease of installation and increased speed of drilling operations. The variable-voltage system gives all these and the added advantages of the smooth high-torque variable-torque speed operation of the d-c motor.

P. L. Savage (nonmember; General Electric Company, Los Angeles, Calif.): I am sure we all are indebted to Mr. Lamberger for a very excellent paper on a subject which should be of great interest to the petroleum industry in particular and electrical engineers in general. In the writer's opinion, d-c equipment using variable-voltage control offers many advantages which are covered in considerable detail by Mr. Lamberger and should find more general use in the oil fields.

As suggested by Mr. Lamberger early in his paper, variable-voltage drilling is usually associated with internal-combustion engines. He also mentions that steam turbines and a-c motors have been suggested as prime movers but up to the present time, have not been used. A-c motors for generator drives, instead of engines, in particular, seem to offer a number of advantages which should be given serious consideration by the purchasers of oil-well-drilling equipment.

It must be admitted at the start that some locations where drilling operations are carried on, do not have a-c power available and in these locations, prime movers are to be favored. On the other hand, substantial percentage of oil-well drilling is done in locations where central-station power is available at reasonable cost. In such cases, the use of motor generator sets consisting of an a-c motor, of either the induction or synchronous type, driving the d-c generators, should be given careful scrutiny. Available central-station power lines are usually more than ample in capacity for the electric power requirements in drilling the deepest oil wells.

In this discussion, I would like to point out briefly the advantages of a-c motors when used for driving d-c generators.

It is generally admitted that the a-c motor has an advantage over the reciprocating engine on the basis of maintenance costs.

Ease of installation and portability are other factors which favor a-c motors to drive the generators, due to smaller size, lighter weight, and fewer auxiliaries.

Other considerations in favor of motor generator sets are:

1. No water for cooling is necessary.
2. There is no fuel problem.
3. The utility factor is practically 100 per cent.
4. More power per pound weight and per square foot of floor area occupied.
5. Lower first cost.

Many operating companies find it necessary to move drilling rigs from one field to another and in some cases, these new locations may not have a-c power available. This presents no serious problem since an a-c motor might be replaced with an internal-combustion engine for such locations. In the original design the d-c generators can be chosen so that the operating speeds are suitable for either motor or engine drive.

Mr. Lamberger has very clearly pointed out the advantages in the use of variable-voltage d-c power for drilling and has compared this operation with engines and mechanical transmissions.

In the past, where alternating current is available, it has been the practice of some operating companies to use a-c drilling equipment which consists of wound-rotor induction motors for furnishing the required power directly to the draw works and mud pumps.

It should be remembered that the a-c drilling motors obtain their speed variation by means of losses in the secondary or rotor circuit; therefore, a motor which has a full-load efficiency at full speed of approximately 90 per cent, drops immediately to something below 50 per cent at half speed, assuming that the torque remains constant. As the speed goes down, the efficiency drops in almost direct proportion. In addition to low efficiency at reduced speed, a considerable problem is encountered in maintenance, for the controller is required to carry heavy current. Also motor heating becomes a problem.

If d-c equipment were used with power supplied by a motor generator set, all of the advantages outlined by Mr. Lamberger would be available and the over-all efficiency would be expected to be much higher. Although we have interposed a motor generator set and must supply the losses to it, still the efficiency of the motor generator and d-c driving motor are maintained relatively high throughout the load range of the machine.

For instance, the efficiency of a motor generator set of suitable rating for oil-well drilling would be approximately 83 per cent which takes into account the combined efficiency of motor and generator. At half load, the efficiency has dropped to only approximately 80 per cent, which is very high as compared to the 50 per cent efficiency of a wound-rotor induction motor operating at a similar load.

Bearing out Mr. Lamberger's statement that electrical maintenance costs are low when variable-voltage d-c equipment is

used, it may be stated that there are two such engine-driven drilling rigs being operated by a major oil company in California at the present time. Although they were designed for drilling holes approximately 3,500 feet in depth, they have given an excellent account of themselves drilling much deeper holes and during the period since 1931, the expense of maintenance and repair parts for the electrical equipment has been negligible.

W. G. Taylor (General Electric Company, Schenectady, N. Y.): First let me congratulate Mr. Lamberger on his very fine paper which has been carefully prepared and presents the subject in a very interesting manner from a different angle from anything previously published on this subject. I feel sure that this paper will serve to clearly inform all engineers of the interesting and important phases of this application of electric drive with generator voltage control, even though they may not be familiar with the details of operation of oil-well rotary drilling rigs. Some points, which Mr. Lamberger may have touched on only lightly or not at all, have occurred to me as worth adding to round out his excellent presentation.

Essentially there are three major operations on a rotary drilling rig. The first is that of revolving the drill pipe and bit to drill the hole; the second, which occurs simultaneously with the first, is that of circulating mud down through the drill pipe and up outside of it to carry away the cuttings, plaster up the side of the hole to minimize caving, and provide a hydrostatic head to prevent blowouts where high gas pressures are encountered, this mud circulation being handled by reciprocating pumps; and the third operation is that of hoisting the drill pipe out of the hole to replace worn bits, and also putting the pipe back into the ground again, and likewise handling the casing which lines the hole after it is drilled. I mention this to bring out the point that the motor driving the rotary table to revolve the bit and the motor driving the mud pump must be able to operate with entirely independent speed characteristics and both run at the same time, and so a separate generator must be supplied for each because the speed regulation is by generator voltage control. Therefore, on a fully electrified rig, where all of these major operations are performed by motor drives, at least two generators must be used as Mr. Lamberger has stated.

A good many installations have been made where the pump is driven directly by the engines, which also drive a generator to supply power to the drilling motor, thus making what is known as a semielectric rig. As there is only one main motor in such a case and no mud-pump motors, only one generator is necessary.

In pointing out the advantages of a full-electric rig, Mr. Lamberger has mentioned that in some locations it is decidedly advantageous where suitable space near the well is at a premium, such as on steep hillsides. It might be added that another highly desirable location for this type of drive is in marine drilling, where the power equipment must be located on a barge, and where it is therefore not practical to use engines with direct mechanical drives to the rig, unless the piling used for supporting the derrick is greatly extended at considerable expense to provide a foundation for such a drive.

In explaining the relative characteristics of two-field and three-field d-c generators for this service, Mr. Lamberger has pointed out that in a given generator frame the three-field machine will have the advantage of higher free-hook speed resulting from the higher voltage obtained at light current load. High free-hook speed is considered essential in modern deep-well drilling because it shortens the time required to hoist the free hook from derrick floor to the top of the derrick when putting the pipe back into the hole length by length, and so reduces the nonproductive time when the rig is not making a hole. The speed obtainable is dependent not alone on the generator characteristics, but also on the gear and sprocket ratios of the drive from the motor to the hoisting drum, and on the amount of load on the motor which lifting the free hook involves. This load on a medium or heavy rig will amount to lifting a dead weight of from 10,000 to 15,000 pounds at a speed as high as 415 feet per minute in a 92-foot derrick. It is, however, hoisted on the upper part of the volt-ampere curve of the generator, and therefore the relation which the resulting hoisting speed of the free hook bears to the speed of hoisting loads of pipe depends upon the shape of that part of the generator curve. On a two-field generator this part of the volt-ampere curve is steeper than on a three-field design. Not so many years ago when the hoisting speeds for heavy loads were more moderate than they are now, the steeper curve of the two-field machine better fitted the conditions to be met, but since then speeds have been increased for heavy loads, making the flatter curve of the three-field machine better adapted for the purpose. The limit of speed at which the free hook can be hoisted is determined by the human element as represented by the ability of the drilling crew to handle the cycle of operations without a mistake and consequent loss of time which would offset any higher speed used.

Mr. Lamberger has described the difference in motor hoisting characteristics when running from generators in parallel as compared with generators in series. It may be noted, however, that normal hoisting of drill pipe with a properly applied d-c drive of either type is never carried on at the high-torque slow-speed end of the curves, shown in figures 3, 4, and 12, as the speed is too low to get the pipe out fast enough to suit any operator. A drive properly applied both as to horsepower capacity and gear and sprocket ratios should handle a heavy normal hoisting load on that portion of the horsepower-output curve of the motor or kilowatt-output curve of the generator which is at or near the peak output. Under such conditions it has been found, in the cases which have been checked, that the loss of one of two generators operating in parallel to supply the hoisting power will still leave enough torque available from the remaining generator to hoist the pipe at very low speed.

Another point to the advantage of the scheme of running the generators in parallel is that, on the modern four-speed draw works or hoist, only the three higher speeds are used for normal hoisting work, and the lowest speed is therefore available for increasing the rope pull at a given motor torque in an emergency.

There are many equipments in service, some of them designed for the generators to run in series and others designed for them to run in parallel for hoisting, and as far as I know all have given an excellent account of themselves and have met emergency conditions successfully.

A. Naeter (Oklahoma Agricultural and Mechanical College, Stillwater): As an educator in a region where many electrical-engineering graduates enter various phases of electrical work in the oil industry, the writer feels that the author has made a valuable contribution to the available literature on variable-voltage rotary drilling rigs.

During the last few years the writer has been watching with interest a large drilling company in the southwest with regards to its drilling personnel. This particular company uses variable-voltage equipment driven by internal-combustion engines, and direct Diesel drive as well as conventional steam equipment. A few years ago this company hired an electrical-engineering graduate, with oil-field experience, and competent as electrician and machinist, to work as a motorman on a variable-voltage drilling rig. At first this employee faced considerable opposition from the practical men working on the rig. He soon "sold himself" to both employer and employees of the company to a degree that several additional electrical graduates were employed because the employer had become convinced that the electrical graduates had been able both to reduce maintenance costs and to speed up drilling operations. In time motormen became drillers, and then advanced to positions of greater responsibility. No practically trained employees were dropped, but electrical-engineering graduates were employed to fill vacancies, appearing through normal turnover, as well as new positions. Now the company no longer insists on oil-field background, and electrician and machinist skills, but trains its young engineers after employing them. This particular company is following an employment program that in time will place at least one graduate on each tour of every rig.

To an engineer in the educational field, it is encouraging to see young engineering graduates prove themselves in operating variable-voltage rotary drilling rigs at a time when many of the conventional fields of employment of the predepression days offer relatively few opportunities.

E. M. Gerry (Allis-Chalmers Manufacturing Company, Milwaukee, Wis.): In the second paragraph of Mr. Lamberger's paper he states that "*A-c motors* can be used to advantage [as prime movers] and have been proposed, but to our knowledge never actually used."

A well was drilled in Oklahoma several years ago, using d-c variable-voltage equipment, driven by a squirrel-cage induction motor. The final depth of the hole was over 10,000 feet; 7,500 feet of the total depth was drilled with special heavy $6^5/_8$-inch drill stem.

Transactions

Preprint of Papers and Discussions Comprising Pages 257–320 of the 1940 Volume

Some Recent Developments in Impulse-Voltage Testing

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Synopsis: Impulse-voltage testing of electrical apparatus and circuits is a steadily growing practice and constant attention is therefore being given to improvements in testing methods. Accordingly, as progress is made it is necessary to describe recent changes. This paper presents a brief discussion of the present situation, describes some improvements in technique of surge analysis of apparatus and circuits, and in equipment for the generation and measurement of test surges.

EQUIPMENT and methods for impulse-voltage testing of apparatus and circuits have been added to and improved considerably within recent years. In comparison with the older methods, the newest technique provides for several important advantages. A decidedly better understanding of the surge mechanism of the circuit and an improved control of shape and timing of generated surges is now realized. Impulse-voltage tests and investigations are conducted with greater speed and reduced uncertainties.

The Twofold Nature of the Surge-Strength Problem

Impulse-voltage testing in its earliest period consisted in applying a surge voltage, measured for amplitude by the sphere gap, to the apparatus or circuit under investigation and watching for visible evidences of failure. The introduction of the cathode-ray oscillograph,[1] which provided for the recording of voltage wave shapes, opened the way to a more precise understanding of surge performance of circuits and strength of insulation.

At present a complete experimental analysis of the electric impulse or surge characteristic of an electrical machine or circuit will involve two general considerations. These are the surge mechanism of the circuit and the electrical strength of the circuit. Stated in a different way, any experimental analysis of the surge characteristics of a circuit, whether it is a machine winding or a connecting network, must, to be at all complete, answer two questions:

1. What is the nature of the current and voltage variations in the several parts of the circuit under surge conditions?

2. What is the strength of the circuit (insulation particularly) under surge conditions?

As an example, take the case of the rotating-machine winding where entering surges are subject to varied reflections and attenuations. Depending upon such factors as winding length, coil turn distribution, and terminal connections, voltage wave shapes and amplitudes inside the winding will vary widely particularly when the applied surge voltages are relatively short in time duration compared to the electrical length of the winding. To apply an impulse voltage, therefore, in such a case, to test for insulation strength, without an understanding of the surge mechanism involved, may frequently lead to incorrect results. The case of the rotating machine, however, is but one example of the many cases where in an experimental analysis both the surge mechanism and electrical strength of the circuit must be considered.

Oscillograph Electric-Transient Analyzer

Recognizing the importance of providing a measuring instrument for surge analysis which eliminated the delays and difficulties involved in the use of the single-discharge surge generator and high-speed cathode-ray oscillograph, the oscillograph electric-transient analyzer[2] was developed. Several years' use of this instrument has demonstrated its wide applications and has resulted in improvements in the device.

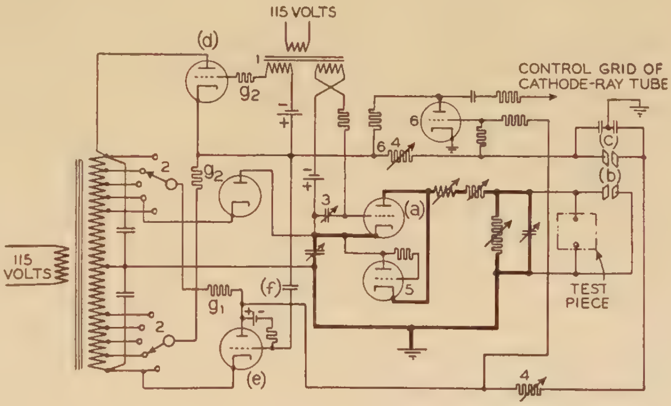

Figure 1. Oscillograph electric-transient analyzer

The oscillograph electric-transient analyzer generates a succession of low-voltage impulses of controlled wave shape for application to the circuit or apparatus to be analyzed for surge mechanism. The time of occurrence of the impulse waves is co-ordinated exactly with the time axis of a cathode-ray oscillograph and there is, therefore, an exact retracing of the wave image on the oscillograph screen. By connecting the deflection plate terminals to a selected point of the circuit under study the wave shape at this point is observed as a standing wave. By moving

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1. For all numbered references, see list at end of paper.

the deflection plate terminal rapidly through succeeding points on the test circuit, the travel of voltage wave shape along the circuit is made visible.

Figure 1 is the connection diagram for the latest analyzer. The circuit changes recently made are noted by numbers as follows:

1. Initiating transformer
2. Time-axis position control
3. Preliminary zero-line control
4. Balanced voltage time-axis circuit
5. Reverse-current tube
6. Cathode-beam control

The low-voltage surge-generator circuit shown in heavy lines produces a surge of adjusted shape for each cycle of the 60-cycle supply voltage. The surge is initiated by the firing of the thyratron tube *a* which in this circuit replaces the sphere gap of the high-voltage surge generator. The surge voltages are applied to the test piece and to the vertical deflection plates of the cathode-ray oscillograph *b*. Now the time axis of the oscillograph which is provided by the horizontal deflection plates *c* must have a correct and fixed time relation to the surges generated. This it was found could best be accomplished by firing the time-axis thyratron *d* from one secondary of the peaking transformer 1 and the surge tube *a* from the other secondary of the same transformer. Tube *d* in turn instantly fires the other time axis tube *e* through coupling capacitor *f*. By means of a capacitor 3 the firing of the surge thyratron *a* may be delayed any desired amount to provide for some zero line before the surge starts.

Most effective use of the cathode-ray-tube screen requires that the time axis begin at a point near the left edge of the screen and sweep to the right. To provide for the beam starting at the left a definite deflection voltage is required. Obtaining this from batteries or fixed-pole magnets has disadvantages. For the analyzer circuit, therefore, a portion of the 60-cycle voltage of the main transformer was utilized. Tap switches at 2 were found convenient for selecting the required beam bias voltage so that at the instant of beam initiation the bias would be correct. Resistors g_1 and g_2 absorb the transformer voltage when thyratron tubes *e* and *d* are tripped.

In the original analyzer the time-axis voltage was supplied through a single tube to one time-axis deflection plate, the other plate being grounded. This was found to have two disadvantages. It prevented good focusing of the cathode beam throughout its travel and it gave a converging deflection sensitivity (direct-voltage lines were not parallel). By using the balanced circuit as shown in figure 1 comprising principally tubes *d* and *e* and in which the time-axis plates have at each instant the same potential but of opposite polarity, these two disadvantages have been eliminated.

For the unidirectional polarity surges a single discharge tube at *a* was shown in the early analyzer circuit to be adequate. However, a number of instances occurred where oscillatory surges were required. For the low voltages utilized in the generator circuit the substitution of a gap was objectionable because of timing difficulties. In addition another discharge tube connected oppositely, as shown at 5, provided for the conduction of the reversed polarity currents accompanying oscillatory discharges of the main capacitor.

In view of preventing undesirable illumination on the cathode-tube screen and back-sweeping of the beam, a good arrangement for beam initiation and cutoff is required. This has been realized by taking off the time-axis circuit at the point marked 6 a positive-polarity voltage which is in part applied to the control grid of the cathode tube as shown in figure 2 and discussed in connection with the cathode-ray oscillograph in a subsequent section.

While the duration of the beam could be controlled by varying the time constant of the initiating circuit, better results are obtained by making the time constant longer than the slowest time axis and cutting off the initiating potential with a thyratron 6. The grid of this thyratron is connected to both sides of the time-axis circuit by resistors of such value that the grid potential becomes positive and fires the tube at the end of the time axis.

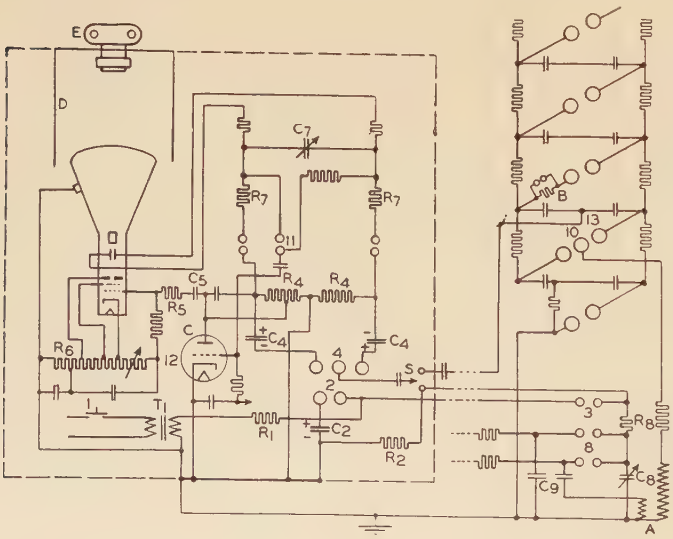

Figure 2. Impulse-generator and oscillograph control circuits

Surge Test of Insulation Strength

Surge-voltage and impulse tests of apparatus and conductor insulation are made with a surge generator, cathode-ray oscillograph and voltage divider, and sphere gap. As regards the generator and oscillograph, recent changes require some explanations.

Cathode-Ray Oscillograph

Some two years ago[3] there was described for the first time a practical high-speed oscillograph which dispensed with vacuum-pumping equipment and permitted simultaneous visual observation and recording of short-time surges. Complete circuit diagrams were presented. Continuous use of this oscillograph on a wide variety of work since then has resulted in many valuable refinements in equipment and methods. The following paragraphs describe the major changes adopted.

The diagram of figure 2 shows the latest arrangement of the control and timing parts and connections for the impulse generator-cathode ray oscillograph circuit. Apparatus and circuit changes are summarized as follows.

A. Substitution of an impulse transformer for an intermediate surge-generator unit.

B. Introduction of a special wave-front circuit giving extra timing precision.

C. More precise beam-duration control.

D. Introduction of extra light shielding for camera compartment.

E. Utilization of higher-speed camera.

In all high-speed cathode-ray-oscillograph work and particularly with non-recurring transients the problem of properly timing the oscillograph operation with the event to be recorded is an important one. In general impulse testing

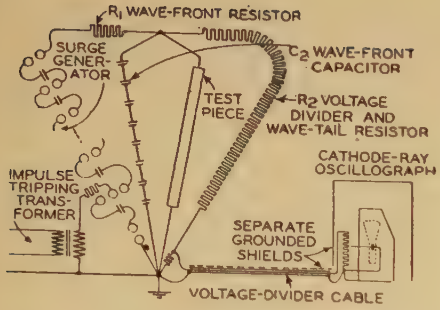

Figure 3. Schematic arrangement of surge-generator circuits

the total duration of commonly used time axes ranges from 1 to 100 microseconds. For full-time flashover on a standard wave such as th e$1^1/_2$x40 microsecond suitable time axes range from 50 to 100 microseconds and for the 1x5 wave from 5 to 10 microseconds. For some volt-time flashover curves and for wave-front work, time axes of total duration as low as 1 microsecond are sometimes required. For best results a short-time zero-deflection axis is required prior to the beginning of the recorded transient. For full-time flashover work with a 50-microsecond time axis, this zero-deflection time axis will be several microseconds long. Adequate time co-ordination between the time axis and the transient will be within one or two microseconds. However, for wave-front testing the zero-deflection time axis will be less than a microsecond and adequate time co-ordination will require a precision within tenths of a microsecond. For this reason a particular connection arrangement is used for full-time flashover work and a second connection for wave-front work. Changing from one connection to the other is accomplished by reversing the switch S on figure 2.

For full-time flashover tests S is turned down. The initiating switch 1 when closed provides for a power frequency voltage on the right sphere of gap 2 of the initiating surge circuit. As the left sphere already has on it a continuous voltage of positive polarity, this gap breaks down and is immediately followed by the breakdown of gap 3. Gaps 2 and 3 are in series and really constitute a three-electrode gap. They have been separated as shown so that the ultra-violet radiation from gap 2 will irradiate gap 4 and gap 3 will irradiate gap 8. Gaps 3 and 8 in turn are placed so as to irradiate the main-generator trip gap 10. Such irradiation produces ionization in the gaps so that they spark-over without delay when the potential on them reaches the spark-over value.

The voltage of capacitor C_2 is now applied across resistor R_2 through the switch S to the midsphere of the time-axis-circuit gap 4. Capacitor voltages C_4 are applied across resistors R_4 and a square-wave positive-polarity voltage is applied to the biasing grid of the cathode tube through R_5. This positive voltage is sufficient to reduce the negative blocking grid bias obtained from the main cathode excitation resistor R_6. The cathode beam is initiated and begins to deflect immediately in accordance with the time-axis voltage of capacitor C_7 which is charging from capacitors C_4 through resistors R_7.

Meanwhile the voltage across resistor R_2 is also across resistor R_8 and capacitor C_8. When the voltage C_8 rises to a predetermined value gaps 8 break down throwing capacitor voltage C_9 on the primary of the impulse transformer A. The resistance-capacitance product R_8C_8 is adjusted to give the required time interval between the beginning of the time axis and the transient excitation of the impulse transformer. The voltage wave on the secondary of the transformer is applied to the mid sphere of the three-electrode gap of the surge generator 10 and precipitates this gap breakdown which is immediately followed by breakdown of the remaining gaps of the Marx circuit and the production of the required surge voltage.

The impulse transformer is an air-core transformer of the type commonly used on damped-wave oscillators. Such a transformer has been found by experience to provide a simple, economical intermediate unit to replace the complete small-scale rectifying-type surge generator commonly used for this purpose. In view of the limited energy output of the transformer, best results are obtained if it is installed at the base of the surge generator and capacitance values are kept low to provide as square a voltage wave as possible. Returning now to the cathode-beam control, a circuit connected to and controlled by the sweep voltage is used to cut off the cathode beam after it has moved off the tube screen. Gap 11 is set to break down when the sweep voltage reaches a value high enough to complete the time axis and in so doing energizes the grid of thyratron 12 positively, causing it to fire and to short circuit the positive cathode-tube grid bias from the sweep circuit used to initiate and hold the cathode beam on. The cathode-tube grid immediately goes back to its negative polarity bias obtained from R_6 and the sequence of events is completed.

As the above described time-co-ordination mechanism is not adapted to split microsecond timing precision, a different technique is used for time axes of very short duration.

When switch S is turned up pressing control button S_1 breaks down gaps 2, 3, and 8 in order and finally gap 10 through the impulse transformer. As yet the oscillograph has not started. Experimentally it has been determined that the insertion of a low resistance at B in the surge generator circuit will provide sufficient delay in the breakdown of the Marx circuit gaps to permit the tripping of the sweep circuit gap 4 and the completion of the entire mechanism of cathode-beam initiation and initial zero-deflection sweep through a connection at 13 on the second stage of the surge generator. This arrangement provides for all the precision required in timing, succeeding surges occurring within 0.1 microsecond on the time-axis scale. The resistance B is bridged by a gap which breaks down to carry the main discharge current of the surge generator.

Surge-Generation Circuits

Recent increasing use of wave-front tests wherein time elements to be measured range as low as 0.1 microsecond at high voltage and 0.02 microsecond at low voltage have necessitated that more attention be given to the arrangement of surge-generator discharge circuits to eliminate spurious oscillations. Experience has gradually shown that the general considerations for reasonably smooth waves are as follows:

1. The ground point of the surge generator, oscillograph, test piece, and resistance voltage divider to converge as nearly as possible to one point as shown on figure 3.
2. The cable from the resistance divider to the oscillograph to be out of the generator field.
3. The oscillograph to be housed in shielded room and this room to be as well out of the field of the generator as possible.
4. The ground point to be as directly connected to good ground earth as possible, a few feet (less than ten) if possible.
5. Both ends of the divider cable to be terminated by a resistance equal to the surge impedance.
6. Several hundred ohms damping resistance in the deflection leads.

In figure 3 are illustrated several of these points. The diagram is not intended to show relative positions of apparatus as these are invariably peculiar to each installation. The practice of converging all ground connections at one point has been found to eliminate stray potentials in any one circuit due to the

ground connection of that circuit carrying ground current for another circuit. This has been shown to be important particularly in connection with the measurement circuit to the oscillograph.

A frequent source of disturbance in the measurement circuit is an oscillation re-

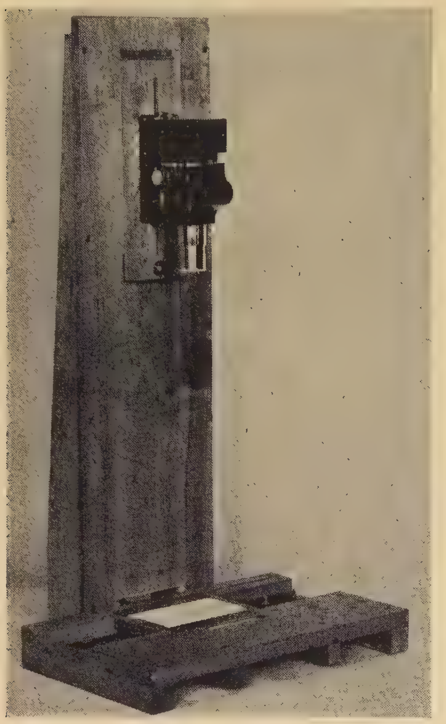

Figure 4. Projector for reproduction and analysis of cathode-ray-oscillograph film

sulting from the stray-capacitance coupling of high-voltage elements with the divider cable sheath. This can be eliminated by a shield as shown in figure 3 or by running the cable under the ground-floor level. If the oscillograph housing is located in the field of the high-voltage elements, local oscillations may occur in it for each surge-generator discharge. A separately grounded shield over the housing is therefore beneficial.

A most important feature is a good short ground connection between the common point and ground. In fact, for high-voltage unbalanced discharge circuits, whether or not satisfactory short-time tests can be obtained will depend upon grounding conditions.

The resistance equal to the surge impedance at the oscillograph cable end provides for the elimination of reflections. This resistance should be carefully adjusted. However, experience has been that complete elimination of reflections is difficult. The resistor at the generator end of the cable is therefore advantageous as it provides against repeated reflections appearing at the oscillograph end.

Film Records

The high-vacuum type of oscillograph permits records of any size desirable depending upon the camera used. Experience however, has been that standard 35-millimeter records are most convenient and accurate. As each wave is observed visually, as it is recorded photographically, qualitative results are known before films are developed. With the small film records which can be dried in less than ten minutes after washing, inserted in a standard projector as shown in figure 4, the wave shape is projected on the lower table surface which is provided with cross-section lines. Direct calibrations are first made by projecting the calibration oscillogram. This provides a ratio of kilovolts per millimeter deflection which can be used repeatedly for the measurement of test oscillograms.

When film reproductions are required, and these usually necessitate some marking such as identifying numbers or scale division values, the wave image from the projector is transmitted through a transparent surface just above the table level. Such markings as necessary are made on this surface which a quick-drying ink. An unexposed film is inserted under this transparent surface and the image of the wave shapes and markings recorded usually at five times the size of the original negative. As this enlargement is really a positive film, prints from it will be as desired—black traces on a white background. Any number of paper-print reproductions are now made from this positive film without hazard to the original record.

Detection and Location of Faults

Because impulse tests involve voltage applications of only a few microseconds time duration, it is often difficult to know when failure has occurred or damage has been done to the test specimen. Especially is it important to know this immediately on application of a surge so that testing may be discontinued until the location or nature of the failure is determined. The most common and practical evidences of failure or damage are as follows:

1. Visible external arcs and corona streamers.
2. Excessive noise in the discharge.
3. Chopping or distortion of the oscillogram.
4. In oil-immersed apparatus, rising gas or smoke bubbles.
5. Indications of excessive current in the test leads.

Visible external arcs and corona streamers are present in most cases of insulator flashover such as porcelain insulators when tested for full-time flashover, or when volt-time curves are being taken. Corona streamers are visible at voltages below flashover and beginning usually on the rising front of the wave continue in extension as the voltage increases. The formation of these streamers, however, apparently lags behind the applied voltage and their extension continues for a time along with the dropping voltage of the wave tail. If the level of voltage of the wave is sufficiently high, these streamers bridge across the insulation and culminate in flashover. The critical

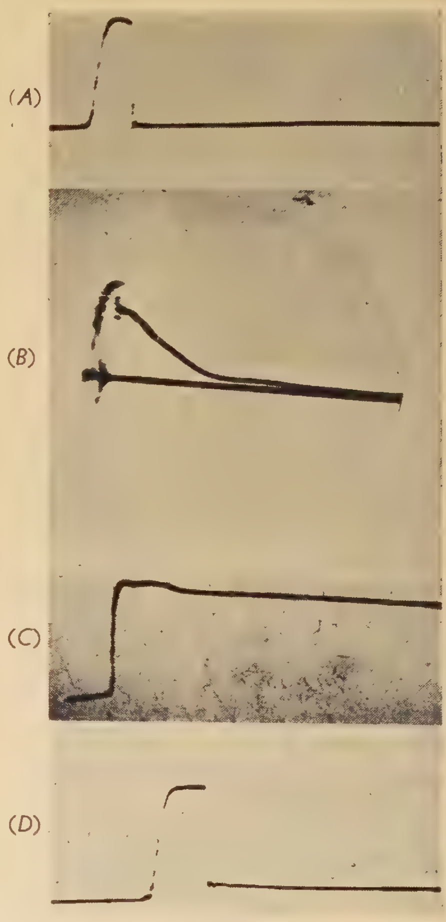

Figure 5. Sample oscillograms of insulation failure

A—Insulation failure on a wave tail showing the complete chopping obtained in a low-resistance breakdown

B—Insulation failure on a wave crest showing partial chopping obtained in a high-resistance breakdown

C—Partial insulation failure of a high-voltage cable as indicated by wave distortion on the crest

D—Complete insulation failure of a high-voltage cable on the next application following C

flashover is that of the lowest voltage level (crest voltage) which will complete flashover for about half the impulse applications. No difficulty is experienced in detecting flashover in such cases. Both visible flashover arcs and excessive noise give ample evidence of it. The flashover path shows the failure channel if the observer is watching the test piece carefully.

On wave-front tests, however, and for some cases of chopped waves additional difficulties are encountered. The chopping of the wave adds a volume of noise which renders this method of no value as an indicator, and distorts the test wave so that the oscillogram of the chopped wave cannot be used with any degree of certainty to indicate test-piece failure. It is always necessary to follow up the chopped wave with a full wave of the same voltage level. The full wave of a specified voltage level has a crest voltage 15 per cent lower than in chopped waves.

Chopping or distortion of oscillograms in full-wave tests are the most practical and certain indications of damage to the insulation under test. A sharp drop in the wave such as shown in figure 5*A* definitely shows that failure has occurred. This is the record of a failure in an air-insulated instrument transformer which could not have been detected by outside evidences or by excessive noise. This failure occurred from line-to-ground and took the form of a very low impedance failure path. Figure 5*B* shows a distorted wave indicating partial failure.

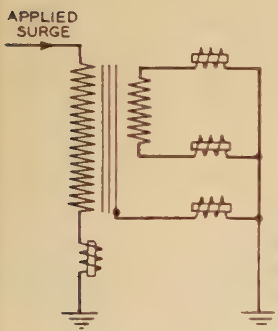

Figure 6. Arrangement of magnetic links for location of failure points

Figure 5*C* is an unusual and interesting oscillogram of a cable failure showing a wave distortion due to partial failure on the surge preceding the one causing final breakdown, which is shown in figure 5*D*. Such records are not frequently obtained and their occasional occurrence stimulates confidence in the oscillograph.

Observation of the oil surface in oil-immersed apparatus sometimes is helpful in detecting and locating a failure, but in general is a very unsatisfactory method because small failures which can be detected from the oscillogram often do not result in rising bubbles, which can be seen on the surface of the oil.

In all these records the chopping and distortion of applied full waves are immediately observed on the screen of the high-vacuum oscillograph.[1] Although not infallible the oscillograph is the best evidence of damage. Simultaneous visual and photographic recording of the voltage wave shape across the test piece insures the detection of failures immediately. Time lost in testing and resulting confusion when surges are applied after the first failure can be avoided when each test-piece voltage wave can be observed as it is applied.

In many cases of impulse-voltage testing the test piece is made up of a number of parts such as several windings and possibly a core and a case. The most common practice is to apply the impulse to one winding with other windings and core and case grounded. It is always important to know when failure occurs just which insulation has been broken down. Particularly in connection with instrument transformers the authors have made many successful uses of the surge-crest-ammeter magnetic-link technique[4] commonly used for lightning measurements.

If as shown in figure 6 the connecting leads to the several parts of the test piece are brought through magnetic-link stations, the links can be used to indicate where breakdown occurs. As soon as the oscillograph indicates breakdown by chopping or distortion of the wave, the magnetic links are measured for residual magnetization in the surge-crest ammeter. If properly adjusted the magnetic links in the path of the failure current will receive greater magnetization.

Small coils such as shown in the figure have been used most commonly for this application. Two, three, six, or ten turns are used. The calibration curves for unidirectional surges are shown in figure 7. Depending upon the characteristics of the surge-generator circuit and the shape of the wave applied, the coils will carry normal capacitance current which increases in amplitude with applied voltage. Therefore, the magnetic link coils must be chosen to leave no link magnetization for these charging currents, but to provide sufficient turns to give measurable residual for the short-circuit currents.

Oscillographic Recording of Voltages Between Tap Points

While the greater portion of impulse testing is concerned with voltages between high-potential tap points and ground in very many cases direct tap-to-tap voltage increments are required. This requirement calls for the measurement of low-voltage increments at high-voltage levels. With the deflection plates of the oscillograph either directly connected or through resistance or capacitance dividers, both plates become of the same voltage polarity. When the voltage between plates is sufficiently high for a suitable deflection, the absolute potentials of the plate will be excessive for good oscillograph operation, that is, absolute deflection-plate voltage will introduce a cathode-beam distortion which results in beam defocus and unsatisfactory records.

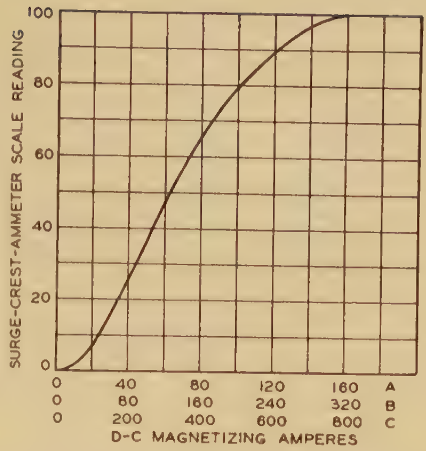

Figure 7. Surge-crest-ammeter magnetic-link calibration

A—Ten-turn coil
B—Five-turn coil
C—Two-turn coil

Until recently such tap-to-tap voltages have been obtained by subtracting tap-to-ground records or by accepting usually with considerable uncertainty such tap-to-tap records as could be obtained with minimum defects. The method of subtracting tap-to-ground measurements is unsatisfactory because of possible uncertainty in the timing of the two records, a point on which the actual values of tap-to-tap voltages depend.

Through the work of the authors marked progress has been recently made on this problem. A circuit has been built and tested which automatically does the subtracting of the two tap-point waves. Figure 8 is schematic drawing of the connections used for the subtraction divider.

Assuming a requirement of tap-to-tap measurements between T_1 and T_2 at the high-voltage end of the winding W, the applied surges are entering at S. These may be single-surge applications from high-voltage surge generator or a timed train of surges from the oscillograph electric-transient analyzer.

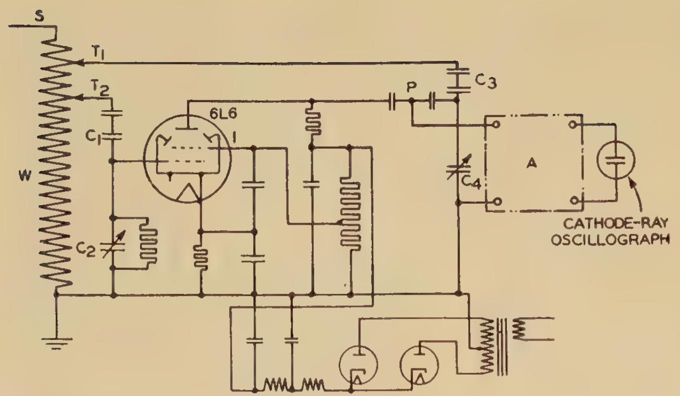

Figure 8. Subtractive voltage - divider circuit for tap-to-tap records

Capacitor combinations C_1, C_2, and C_3, C_4 are similar voltage dividers which must be sufficiently low in capacitance to give no appreciable wave distortion at the intermediate tap point. This is an important and exacting requirement.

Unit I is an amplifying inverter and A an amplifier. At point P the voltage waves from the left and right divider superimpose and are of opposite voltage polarities. The oscillograph through amplifier A, therefore, records the voltage between P and ground which is equal to the instantaneous differences between the voltages at P from the left and right dividers.

Preliminary adjustment of this circuit is accomplished by connecting the tap point terminals T_1 and T_2 together at T_1 and adjusting C_3 and C_4 for no deflection on the oscillograph. This proves a correct balance of the two waves arriving at P. Moving the left capacitor lead to intermediate tap point T_2 now gives the required tap-to-tap voltage difference.

Particular precautions are necessary in setting up such a circuit to provide for accurate results. The capacitance divider should be permanently built in a very symmetrical arrangement to provide for a minimum of unbalanced voltage interference effects, and when in use should be so adjusted that the amplifiers are not carried beyond their saturation points. The inverter must be built to include a minimum of time lag between the incoming grid voltage from the capacitor C_1C_2 and the output plate voltage to point P. The amplifier at A must have a wide-range frequency response and a high input impedance. In balancing the whole arrangement it has been found possible to add sufficient lead length at T_1 to balance against some lag in I which cannot be eliminated otherwise.

Conclusions

Recent rapid progress in impulse testing has emphasized the importance of an understanding of the surge mechanism of the circuit under test and analyzer equipment has been developed which provides for direct demonstrations of this mechanism.

For the recording of test waves in impulse-voltage testing precision methods of timing have been made available which provide for improved accuracy of recording with the cathode-ray oscillograph, especially for wave-front testing.

The necessity of careful attention to surge-generator grounding conditions has been increasingly recognized and practices have developed wherein disturbing oscillations particularly in the measurement circuit are considerably relieved.

A circuit which permits the recording by cathode-ray oscillograph of voltage increments between tap points at high absolute voltage levels has been designed and tested.

The cathode-ray oscillograph is the best indicator of damage in impulse testing, because it provides for both simultaneous visual observation and permanent film records of test wave distortions and choppings.

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Discussion

Victor Siegfried (Worcester Polytechnic Institute, Worcester, Mass.): Messrs. Foust and Rohats are to be complimented on the thoroughness with which they have reported their progress in this rather specialized art of impulse testing. Their contribution will aid greatly in reducing the intangibles and increasing the real understanding of the behavior of surges in laboratory and field apparatus.

One question is raised by the authors which might bear even more consideration, namely, keeping the potentials of the deflection plates symmetrical with respect to ground. This is discussed in regard to the timing-axis plates for the transient analyzer, and has been provided for similarly in the circuit for the oscillograph, figure 2, where the ground potential lies midway between the time-axis deflection plates. However, would it not be equally important to maintain symmetrical potentials on the vertical (surge) deflection plates? Usual circuits with the resistance divider inherently ground one of these plates, in which case this ideal may not always be practicable. To be consistent, then, the calibration voltage must also be applied with the same plate grounded so that any nonuniformity in sensitivity will apply equally in both cases. Do the authors know of any way of obtaining a phantom ground for these deflection plates?

The practice recommended by the authors of bringing ground points of all parts of the surge generator and measuring circuits together is most heartily subscribed to. As we approach the faster wave fronts comparable with television frequencies, it may be helpful to refer to the parallel experiences of television engineers, whose similar difficulties with stray effects are being remedied by the same procedure.

P. H. McAuley (Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): In reviewing the section on "Surge Generation Circuits", it is interesting to note the different practices that exist in different laboratories. Concerning grounding and shielding, laboratory techniques are very similar. On the other hand, we have seldom used a resistor at the generator end of the divider cable as the authors advocate. It has never appeared necessary, even for short-time measurements, and constitutes another item requiring occasional checking for maintenance of accuracy in results. Similarly, we have avoided damping resistors in the oscillograph deflecting plate leads, always trying to control spurious oscillations at their source in the circuit, rather than damping them out in the measuring circuit. Of course, with capacity dividers it has been found necessary to use damping resistors.

The surge-generator circuit of figure 3 of the paper shows the series resistance R_1, lumped at the generator terminal and a capacitor C_2 connected in parallel with the test piece. With R_1 and C_2 variable, control of the wave front is obtained. Our practice differs in that the resistance R_1 is distributed throughout the main capacitor bank and use is thus made of the natural capacity to space of all parts at high voltage to control the wave front. Particularly for tests with the standard 1.5x40-microsecond wave this method has several decided advantages:

1. Better use is made of the generator voltage rating whereas the addition of terminal capacity definitely derates the generator in voltage. Slightly less series resistance can be used in the latter case but the net effect is appreciable loss in maximum output voltage when a shunt capacitor is used.

2. Making use of the stray capacity of the generator by distributing the series resistance is more logical than adding an expensive capacitor, which is poor economics in most cases.

3. Because of the unavoidable stray capacity, the suppression of oscillations is much more difficult when R_1 is lumped at the terminal. Mathematically and practically it can be shown that R_1 is more effective when distributed along the capacitor bank. This is where oscillations should be controlled rather than in the measuring circuit.

For these reasons, even when a shunt capacitor may be desirable for wave-front control over wide ranges, it is better to have the series resistance distributed.

One point not stressed by the authors is the effect of lead lengths in the discharge and measuring circuits. In 1938 some tests were made at the Trafford laboratory with a 10-inch rod gap in parallel with a 150-centimeter sphere gap on steep-front voltage waves. With the circuits through each gap about 40 feet in length, both gaps flashed on each impulse with the sphere spacing varied between 5.55 and 16.2 inches. At shorter or longer spacings one of the gaps only flashed. This is almost a three-to-one ratio in the sphere gap spacing. When an additional 70 feet was added to the lead to the 10-inch rod gap, 50–50 spark-over between the gaps was obtained for 22.3 inches spacing on the sphere gap and was quite critical. These results illustrate the importance of leads in the testing circuits and their possible effect on measurements. The performance of a rod gap judged by its characteristics as determined at its terminals may be greatly influenced by the addition of a few feet of lead. Conversely, in measuring the characteristics of apparatus on steep-front waves, precautions must be taken to obtain a true picture of the performance.

Morris Newman (University of Minnesota, Minneapolis): Basing our opinion on our own experience we feel in complete accord with the developments in impulse-voltage testing given in the paper by C. M. Foust and N. Rohats. We should like to add the suggestion that the cathode-ray oscillographs with which most laboratories are equipped at present could be simply converted to exterior photography of the

Figure 1. Arrester on 1,000 kv per microsecond

fluorescent screen trace by the use of a miniature 35-millimeter film camera and the recently developed high-speed films. We have taken, for example, using a redesigned cold-cathode-ray high-voltage oscillograph, about 70 oscillograms on a small standard film roll, in test work, just as fast as the surge generator could be recharged, developed the film ready for inspection in five minutes and, after a half-hour of fixing, washing, and quick drying, projected it onto a large eight-foot by eight-foot screen for inspection of minute details. The oscillograph remained ready for instant use in rechecking or for further tests since it was not necessary to disturb the vacuum. We therefore very heartily concur with Mr Foust in recommending the advantages of exterior photography.

Also, while agreeing with the desirability of using symmetrical voltages on the oscillograph sweep plates when possible, we feel that such a measure minimizes the effect of nonuniform fringing field beyond the deflection plates but does not remove the cause completely, although it may do so for most practical purposes. We should like to suggest from experience that linear and constant deflections in both the timing and phenomenon voltage sweeps are obtainable by shaping the field beyond the plates, with a system of shielding surfaces and properly shaped passages, so that the beam electrons emerge through the same field conditions independently of their position in a perpendicular direction to the direction of the deflecting field. With care in controlling the fringing field we have found it possible not only to obtain constant deflection over the full sweep with voltage to just one of the plates, which is generally far more convenient, but we could then move the beam electrostatically instead of electromagnetically into any desired location by application of an easily controllable d-c biasing voltage to the opposite deflection plate.

Finally, we too have found an initiating "impulse transformer", which in our work was a Tesla coil, a useful economical substitute for a separate initiating impulse generator for synchronizing longer-time phenomena; and parallel to our experience we note that Messrs. Foust and Rohats have been quite aware, and have pointed out, that such a scheme would not be suitable for fast fractional-microsecond timing precision. But we do differ on the advisability of obtaining the desired delays for getting the oscillograph into operation through the insertion of the delaying resistance B in figure 2 of the paper under discussion. Such a delay in the impulse-generator switching process will, in fast front-of-wave work show up as a jog in the lower part of the voltage-wave-rise trace As a matter of fact such delays in the first few stages of the impulse generator often occur even without insertion of resistance and we find it indeed desirable to eliminate these delays entirely by simultaneous initiation of the first three or four of the intermediate gaps rather than of only one, in order to obtain a more smooth rate of voltage rise output of the generator (figure 1 of this discussion). Therefore we should recommend a separate initiating surge-generator circuit covering the entire range of synchronization times in preference to the dual range "impulse transformer" and "impulse generator initiation delay" combination scheme if very fast front-of-wave work, such as in the testing of low-voltage equipment, is involved.

The last suggestions of this discussion are offered not in criticism, but as specialized refinements which some laboratories may possibly find will lead to further development of impulse voltage research technique. We feel that C. M. Foust and N. Rohats have done an admirable job of presenting impulse-testing developments which should go far toward eliminating discrepancies still unfortunately to be found in surge testing.

W. F. Skeats (General Electric Company Philadelphia, Pa.): In a recently installed 3,000,000-volt impulse generator, careful attention was given to many of the points mentioned in the paper by Messrs. Foust and Rohats. The general form of this generator is quite similar to that made familiar by the New York World's Fair generator, except that for the lower voltage only 30 capacitors are used and these are arranged in one unit of four columns,

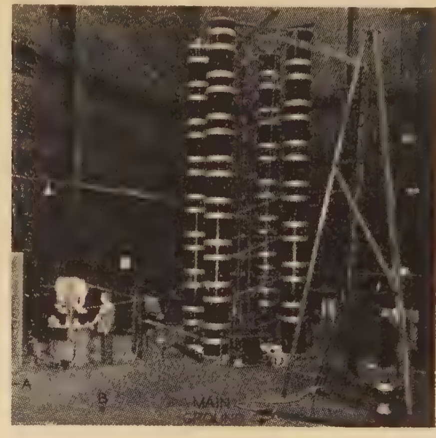


Figure 2. 3,000,000-volt impulse generator

as shown by figure 2 of this discussion. A plan of the layout is shown in figure 3.

Of greatest interest at the moment are the precautions taken in connection with the ground circuit for two purposes:

1. To eliminate spurious oscillations in the cathode-ray-oscillograph record, and

2. To obviate local potential differences in the ground circuit which might be dangerous to personnel or equipment.

The general principles followed in this connection were:

1. Concentration of all grounds at a single point and connection of this point by a short heavy conductor to a good earth ground.

2. Avoidance of all parallel ground connections except as required in laying more than one conduit between two points; in such cases all conduits were kept within a few inches of each other throughout their length.

3. Enclosure of all control-power wiring in metal conduit which served as the ground connection between the various parts of the apparatus.

4. Introduction of control-power wiring to the system only at the main ground point.

5. Connections on three sides from the main ground point to the building steel.

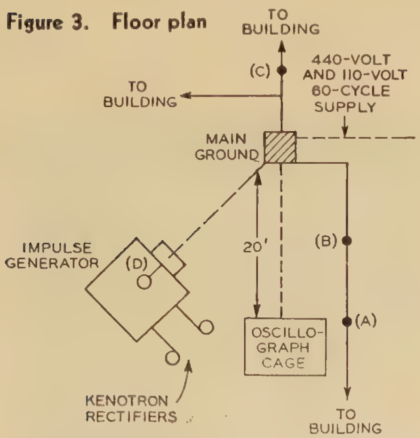
6. Enclosure of the control desk and cathode-ray oscillograph in a metal cage large enough to accommodate the operator and one or two observers This cage used wide mesh screen on three sides and metal sheet on top, bottom, and the fourth side, all solidly connected electrically and grounded by conduit to the main ground. This is in addition to the sheet-metal housing of the oscillograph itself.

7. The deflection lead is a well-insulated concentric cable passing from the main ground to the control cage in a copper pipe from which the cable sheath is insulated except for the connection at the ground end. The control cage is connected to the

copper pipe but the oscillograph housing proper is connected to the cable sheath.

Enclosure of the control wiring in metal conduit gives it good protection from any harmful induced voltage. Electromagnetic induction may cause a potential gradient along the conductor, but except for minute differences due to displacement of the conductor from the center of the conduit or to local irregularities in the magnetic field, the same potential gradient is induced along the conduit. Thus unless there is a conducting path along which current may

Figure 3. Floor plan



Solid lines—Ground conductors on test floor
Dashed lines—Ground conductors below test floor

From main ground, 1 / -inch copper pipe passes through floor, basement, and basement floor to a multiple driven ground

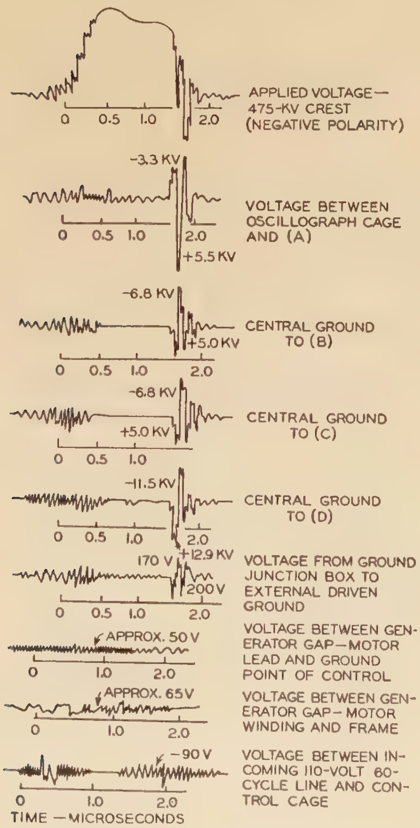


Figure 4. Voltage measurements

flow to relieve the gradient in one or the other, there is no resulting potential difference between them. Such a path has been carefully guarded against. Electrostatic induction may cause a local disturbance of potential, but again conduit and inside conductor suffer the same charge, and by skin effect the current which flows on account of this potential disturbance flows entirely in the conduit. The inductive potential gradient due to this current flow is again equal in both conduit and conductor, leaving only the resistance drop as a source of potential difference between the two. In the oscillograph deflection lead even this resistance drop is eliminated, by the copper pipe outside the sheath.

Thus the potential difference between wiring and the ground system may vary very little throughout the system. In order to keep this potential difference low, owever, one further precaution is necessary: the wiring must enter the ground system at a point where it is subject to but little variation from true earth potential. For that reason, all wiring enters this system at the "central ground point".

In order to check the arrangement, a steep-front wave reaching a crest of 475 kv in about half a microsecond and chopped at about 15 microseconds by a 20-inch rod gap was applied and various voltage measurements made throughout the circuit. The results are shown in figure 4 of this discussion.

These results may be summarized as follows:

1. The most severe voltages occurred at the time of chopping of the wave.

2. Voltages from one to three per cent of the crest value of the applied impulse were measured over comparatively short runs of heavy conductors in the ground system. Most spectacular of these is the voltage of 5.5 kv measured between the control cage and a ground strap running less than a foot away from it and connected over a loop of about 50 feet of heavy conductor. This voltage was checked approximately by means of a sphere gap and found to be correct.

3. The potential difference between the "central ground point" and a driven ground outside the building was limited to about 300 volts—0.06 per cent of the applied wave.

4. The potential difference between frame and winding of the motor for controlling the generator gap spacing, which is located at the base of the impulse generator; the potential difference between leads to this motor and the control cage ground; and the potential difference between the incoming 60-cycle leads and the control cage ground—all were less than 100 volts—0.02 per cent of the applied wave.

Thus voltages within the system are controlled to a satisfactory extent. The relatively high voltage measured on the ground straps connecting with the building steel together with the much lower voltage between the "central ground" and outside earth seems to indicate that the major stray voltages are associated with charges induced on the building steel.

C. M. Foust and **N. Rohats:** Mr. Siegfried discussed the use of balanced voltages in sweep circuits which are necessary to give uniform voltage sensitivity throughout the time axis. With balanced sweeps, d-c calibration lines are parallel, with unbalanced sweeps d-c lines converge. Having a balanced sweep, a balanced deflection voltage would be desirable only from the standpoint of improving the focus. The authors have thought of two ways to obtain symmetrical deflection potentials but have not tried them as both would detract somewhat from accuracy. One way was to place the main ground point at the midpoint of the portion of the resistance divider connected across the deflection plates. In this case the current flowing in the part of the divider between ground and the surge generator would be different from that between ground and the divider because of the addition of charging currents returning from the surrounding building structure. The other way was to leave the main ground at the end of the deflection resistance and connect the oscillograph ground to its midpoint. In this case the oscillograph would be raised to one-half of the deflection voltage, thereby drawing some charging current from the divider. It is possible, however, that this would be negligible especially with a low-resistance divider.

The surge-testing equipment at Philadelphia described by W. F. Skeats incorporates ground-connection arrangements designed with great attention to detail, in view of giving a minimum of circuit oscillations and measurement circuit disturbances. The authors wish to thank Mr. Skeats for his contribution to this discussion.

Morris Newman's comments on outside photography bring to attention a number of interesting considerations. Since the fast cameras required have a very shallow depth of focus the screen would have to be essentially parallel to the film. In this position it could hardly be perpendicular to the central position of the cathode beam and this would mean some correction of the record. Another way would be to have a mirror somewhere between the camera and the screen.

The authors are heartily in agreement with the suggestion of shielded deflection plates, but a tube with such plates is not at present commercially available.

In regard to the use of a delay resistance within the surge generator for wave-front work, the authors' experiences have been that serious oscillations are not obtained. Another simple circuit arrangement has been worked out by J. W. Beatty of Philadelphia. This involves using the initiating impulse transformer the same as for slower work but having several microseconds delay in the oscillograph sweep circuit to counterbalance the delay in the tripping of the surge generator. This delay is obtained by coupling the mid sphere of the sweep trip gap to the initiating circuit through resistance instead of capacitance. The delay may be varied by adjusting the gap setting. This scheme in addition to doing all that the previous method could do has the added advantage of being able to retard the sweep so much that instead of spreading out the front of a wave on the screen some later section of the wave, such as the flashover part, may be brought out in detail. To minimize delays in the spark-over of the first several gaps of a surge generator, they should be arranged in line so that the ultraviolet radiation from the first gap will fall upon and ionize all of the remaining gaps.

The authors appreciate the comments of P. H. McAuley pertaining to the measurement and discharge circuits. The impor-

tance of surge impedance at both ends of a resistance-divider cable varies directly as the length of the cable. With cables of about 50 feet or less only the oscillograph end need have surge impedance across it. With cables of 20 feet or less, the value of the resistance across the cable becomes of no importance. The 200 ohms damping resistance shown in the deflection plate leads are too small to damp any oscillations of such frequency as may arise in the generator circuit, but are enough to suppress such high-frequency local oscillations as may arise in the deflection plate circuit.

With reference to the location of the series resistance in the surge-generator discharge circuit, the authors have found in practice that about 200 ohms distributed within the generator and the remainder R_1 placed externally give the best results. While the economic question of surge-generator efficiency is important, it is secondary to that of good waves and consistent results. On this basis the amount of resistance R required for control of oscillations generated within the capacitor bank was determined experimentally and this resistance was distributed in 20 resistors, one on each side of the ten interstage gaps in use. From this point on, the important considerations are the generation of the required wave shape, its maintenance at all voltage levels, and consistency of test results. Here the authors' experience has been that the value of capacitance across the test piece is quite significant especially for short-time tests and that extra load capacitance C_2 ranging up to ten per cent of the generator capacitance for most work and on special occasions up to 25 per cent is of decided value and justifiable despite some loss in generator efficiency. With values of generator capacitance C_1 and load capacitance C_2 in mind, the oscillograph electric-transient analyzer is used to determine the series resistance $(R+R_1)$ and parallel resistance R_2 for the wave required. With R_1 outside the generator bank, it can be conveniently changed for any wave required.

The efficiency of a generator is dependent upon wave-shape requirements. If the load capacitance C_2 consists only of generator stray capacitance, the series resistance $(R+R_1)$ must be high and efficiency suffers just as much as if C_2 were high and $(R+R_1)$ were low. With a high C_2 made up of extra load capacitance in parallel with the test sample, the wave shape will be more rigidly maintained as both high capacitance and low resistance make possible higher currents into the test piece for corona and flashover streamers. In view of the high energy rates involved in disruptive discharges, it is reasonable to expect the more rigid circuit to give values nearer that required and certainly more satisfactory for comparison purposes.

In considering comparative results it is important to bear in mind that two circumstances are involved, one having to do with comparative results on different apparatus and involving the basic question of insulation co-ordination and the other having to do with comparative results between laboratories on the same apparatus and involving testing equipment and measurements. Results are comparable only in so far as applied waves are similar at all voltage levels.

Load-Rating Theory for Multichannel Amplifiers

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Synopsis: The amplifiers of multichannel telephone systems must be so designed with regard to output capacity that interchannel interference caused by amplifier overloading will not be serious. Probability theory is applied to this problem to determine the maximum single-frequency output power which a multichannel amplifier should be designed to transmit as a function of N, the number of channels in the system. The theory is developed to include the effects of statistical variations in the number of simultaneous talkers, in the talking volumes, and in the instantaneous voltages from speech at constant volume.

In a perfect multichannel carrier telephone system, each channel would be entirely free from interference produced by the energy present in the other channels. Since all the channels are amplified by the same repeaters, which as a practical matter cannot have perfectly linear characteristics, this is an ideal that may be approached but not completely realized. The interchannel interference must be kept down to a value which will be satisfactory for the grade of transmission concerned, further reduction being uneconomic. To do this the repeaters must meet definite load-capacity requirements and modulation (nonlinearity) requirements. The load-capacity requirement is most conveniently specified in terms of the maximum single-frequency sine-wave power which a multichannel amplifier must transmit without appreciable overloading. The modulation requirement pertains to the performance of the amplifier for impressed loads equal to or smaller than the load capacity, and specifies the allowable power in the modulation products resulting from such loads. Because of the numerous factors which affect these requirements, their determination is a rather complicated matter and the present discussion will be restricted solely to a determination of the load-capacity requirement. The object is to determine this quantity as a function of N, the number of channels in the system.

The criteria ordinarily used for determining the load capacity of single-channel amplifiers are of little use here because of two fundamental differences between single-channel and multichannel systems. In the first place, the modulation produced in a single-channel amplifier depends only upon the input to that channel and occurs only when the channel is energized. In addition, the most important frequencies resulting from modulation fall directly back upon frequencies already impressed and the net effect appears as a distortion of the original input, rather than as noise. The situation is entirely different in a multichannel system. In this case, the modulation products falling into one particular channel are in the main unrelated either to the impressed frequencies or to the volume of impressed speech in that channel. Thus it is no longer possible to think of the interference as distortion; the effect must rather be considered as that of a particular kind of noise whose level depends upon the load on the other channels of the system. For a given grade of service, the ratio of signal to noise must be much larger than the ratio of signal to modulation products resulting in distortion; thus it is to be expected that the nonlinearity requirements will be more stringent for multichannel operation than for single-channel operation.

The second fundamental difference between single-channel and multichannel systems arises from the character of the load which each system must be designed to handle. A single-channel amplifier must be capable of handling one channel at the maximum volume normally expected. Inasmuch as the amplifier will be loaded only about one-fourth of the time, even in the busiest hour, and as the averaged impressed volume will be some 15 decibels below the maximum that must

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Many members of the Bell Telephone Laboratories, in addition to those mentioned in the text, have contributed to various phases of this work. The authors take this opportunity to acknowledge their indebtedness to these colleagues, and in particular to Doctor G. R. Stibitz, who first developed the theoretical approach here used.

be provided for, the ratio of maximum to average load of such an amplifier is inherently very high. In a multichannel system, however, the several channels will very rarely be heavily loaded simultaneously. There is thus a favorable diversity factor, increasing with the number of channels, and multichannel amplifiers may accordingly be worked successfully at lower ratios of maximum to average load.

Occasionally, of course, there will be short periods of excessive loading during which the interchannel interference in multichannel systems will rise above the value normally permitted. This sort of thing often occurs when it is desired to make economical use of facilities of any kind in common. In machine-switching systems, for example, it is common practice to associate a large number of lines with a smaller number of switches and trunks. The number of switches and trunks provided is sufficient to ensure a satisfactory service, with a very small probability of requiring more facilities than are available. The multichannel amplifier problem presents a situation identical in principle, though the methods of solution are necessarily very different. The application of probability theory is evidently indicated as the method of attack.

Those characteristics of multichannel amplifiers which are important to the problem will be described first. Then a description will be given of the variables which must be taken into account in computing load capacity. Finally, the combined effects of these variables will be determined on a statistical basis to establish the required load capacity as a function of the number of channels in the system.

Characteristics of the Multichannel Amplifier

At the present time, multichannel systems of primary interest employ single-side-band transmission; the carrier frequencies are largely suppressed and different amplifiers are used for the two directions of transmission. For such systems negative-feedback amplifiers have outstanding advantages, particularly with respect to stability of gain and reduction of modulation effects, and are thus being used almost exclusively in present-day multichannel systems. The following discussion is related particularly to such systems, although many of the calculations are also applicable to less common types.

At light loads the principal modulation products in a negative-feedback amplifier increase approximately as the square or the cube of the fundamental output power. Beyond a certain critical point, however, the modulation increases very rapidly and the total output of the amplifier soon becomes practically worthless for communication purposes. This critical point will be called the "overload" point. For most tube circuits it is either the point at which grid current begins to flow, or that at which plate-current cut-off occurs. This point obviously defines the instantaneous load capacity.

Below the overload point the higher-order modulation products are negligible in comparison with second- and third-order products, and the interference may be regarded as due to the latter sources alone. Beyond the overload point, however, the higher-order products become important very rapidly and the resultant disturbances appear in most, if not all, of the channels. With given tubes, the interference below the overload point may be altered by changing the amount of feedback. The interference above the overload point, however, may be little changed in this way because of the rapid loss of feedback as the amplifier overloads. Accordingly, in designing an amplifier, the necessary load capacity may be determined solely by insuring that the output will rarely rise above the overload point, afterward adjusting the amount of feedback so that the interference below the overload point will be tolerable. There are thus two problems which may be handled separately, at least for negative-feedback amplifiers, it being understood that the results are combined in the final design. As previously stated, only the load-capacity problem will be considered in detail here but many of the methods used have been applied successfully to the interchannel-modulation problem.

The Load on a Single Channel

The total load applied to a multichannel amplifier varies rapidly between widely separated limits. A complete knowledge of the variations in the load applied to a single channel is necessary first; these variations arise from several recognizable causes which may be discussed separately.

Number of Active Channels

First of all, a single channel at a given instant may or may not be carrying speech; if not, it contributes nothing to the multichannel load. A channel will be called "active" whenever continuous speech is being introduced into it; that is, a channel is active during the time it is actually carrying speech power, and also during the short pauses that occur between words and syllables of ordinary connected speech. A channel is said to be "busy" when it is not available to the operator for completing a new call. Busy time is by no means all active time, for a busy channel is inactive during much of the time the connection is being completed, during pauses in the conversation, and finally during the time the other party is talking. The fraction of time during the busiest hour that a channel may be busy depends on the size of the group of circuits of which it is a member and on the methods of traffic operation. Measurements on circuits in large groups, made by M. S. Burgess, indicate that the largest fraction of the busiest hour that a channel may be active is about one-fourth. For channels in small circuit groups, this figure may become considerably smaller but it is unlikely that

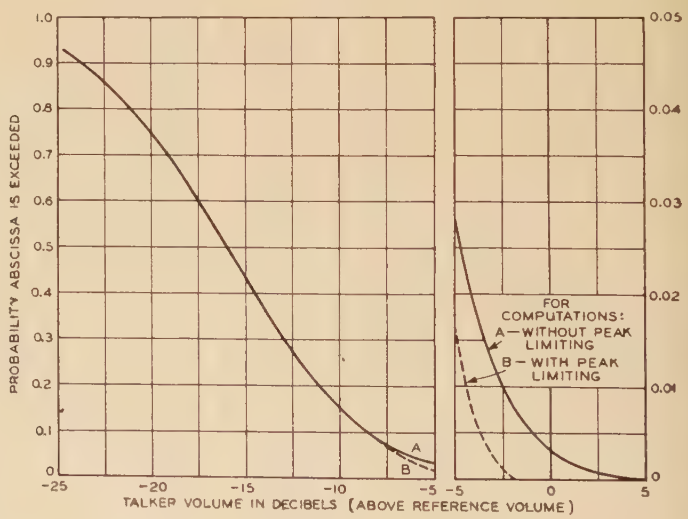


Figure 1. Talker volume distribution

any probable increase in group size or improvement in operating practices will increase it appreciably. This figure, which will be represented by τ, may accordingly be taken as a conservative estimate of the limiting probability that a channel will be active in the busiest hour.

The number of channels that are active at a given instant in an N-channel system may be anything from zero to N. Inasmuch as the channels are independent, it is possible to write down at once

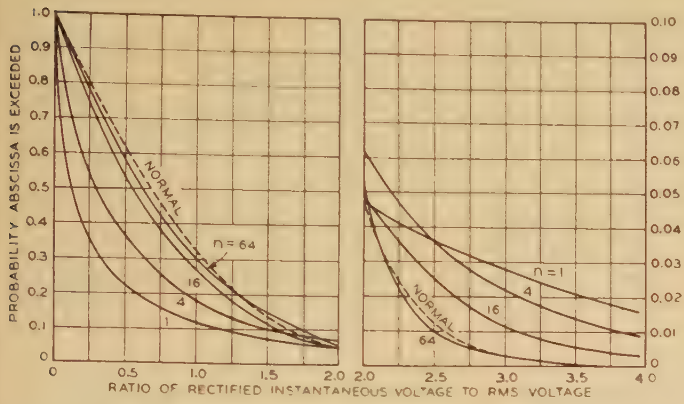


Figure 2. Instantaneous voltage distributions for n talkers

the probability that exactly n of them are simultaneously active. This probability is

$$p(n)=\frac{N!}{n!(N-n)!}\tau^n(1-\tau)^{N-n} \qquad (1)$$

Talking Volumes

A second source of variation in the load on a given channel is that the impressed volume may have any value within rather wide limits when a channel is active. By "volume" is meant the reading of a volume indicator of a standard type. Its importance in the present problem arises from the fact that the volume is an approximate measure of the average speech power being introduced into the channel. Although some other instrument might give a better measurement of the latter quantity, only the volume indicator has been used sufficiently widely in the plant to give data on the distribution of average speech power per call under commercial conditions. The average speech power is dependent on the type of instruments, the character of the speech, and the time interval over which the average is determined. From an analysis of phonograph records of continuous speech it is found that the average speech power of a reference volume talker may be taken as 1.66 milliwatts, and the relationship between volume* and average power may be expressed by the following equation:

$$\text{Volume (decibels)} = 10\log_{10}\frac{\text{average speech power in milliwatts}}{1.66} \qquad (2)$$

This equation is based on the long-average speech power. It will be understood that for purposes other than load-rating computations, a different relation might be found more suitable.

The use of equation 2 to relate volume to average speech power is applicable to speech in a single channel. It is convenient to refer to a quantity related in the same way to the total average power contributed by a number of channels as the "equivalent volume".

The single-channel volumes on commercial circuits are conveniently measured at the transmitting toll test board, which will be taken as a point of "zero transmission level". Henceforth it is assumed that there is no gain or loss between this point and the output of the amplifier, so that the latter is also a point of zero transmission level. While this will seldom be the case in an actual system, the necessary change in the load capacity is easily computed. The volumes at this point are found to be distributed approximately according to the "normal" law; that is, the probability that the volume will be between V and $V+dV$ is given by

$$p(V)dV=\frac{1}{\sqrt{2\pi}\sigma}\epsilon^{-\frac{(V-V_0)^2}{2\sigma^2}}dV \qquad (3)$$

For calls on typical toll circuits, the best present values for the parameters are $V_0=-16.0$ decibels and $\sigma=5.8$ decibels. These parameters depend, of course, upon the character of the local plant and upon the habits of telephone users, and changes in either will affect their values. Curve A of figure 1 shows this distribution of talker volumes at a point of zero transmission level. Curve B of figure 1 is the talker-volume distribution used for load-rating computations when a particular amount of peak amplitude limiting occurs in the terminal equipment. This will be discussed later. Although the mean volume is V_0, the volume corresponding to the mean power of the distribution (3) is equal to $V_0+0.115\sigma^2$, as may be seen by converting the volume scale of the distribution to power ratios, averaging, and reconverting the average to volume in decibels. For the values of the parameters given above, $V_0+0.115\sigma^2=-12.1$ decibels.

* Subsequent to the preparation of this paper, a new volume indicator was standardized for use in the Bell System. With the new volume indicator, volume is expressed in *vu* +8*vu* being approximately equal to reference volume (0 decibels) as used herein.

Instantaneous Voltage Distribution

Finally, the voltage in an active channel fluctuates widely even at constant volume. Not only the differences between successive syllables and the differences between vowel sounds and consonants, but also the fine structure of single sounds, are important in this connection. The total voltage impressed on the amplifier is the quantity which determines whether or not it will overload, and the phases as well as the amplitudes of the frequency components in the several channels must be considered in determining this. It is most convenient for analysis to work directly with instantaneous voltages of speech, the frequency of occurrence of the magnitudes being expressed in the form of a distribution function.

This distribution function has been measured by Doctor H. K. Dunn, using apparatus which measures 4 samples per second of the instantaneous voltage out of a commercial subset and typical loop. By operating the apparatus until about 1,000 successive samples have been measured, usable distribution curves of instantaneous voltage are obtained; this is readily checked by making repeated runs comprising the same number of samples on speech recorded on high-quality phonograph records. It is, of course, known that commercial transmitters have considerable asymmetry as regards positive and negative voltages but the poling referred to the toll board is expected to be random. As the measurements were considerably simplified by doing so, it appeared desirable to average out this asymmetry by arranging a linear rectifier ahead of the sampling apparatus to obtain equal samples of positive and negative voltages.

Such measurements have been made for a number of different talkers, different

commercial subsets, and different volumes, with the speech input held at substantially constant volume in each test. The various subsets now in commercial use all give essentially the same distribution curve. The resulting distributions, if they are considered as functions of the ratio of instantaneous to rms voltage, are also nearly independent of the speech volume at the subset. Specifically, the only important effect of volume is that which may be ascribed to amplitude limiting in the transmitter; that is, to the fact that the transmitter itself has a limited load capacity. However, this effect does not appear until the volume is ten decibels or more above the mean of the volume distribution curve, and is only of importance for talkers at still higher volumes. For all lower volume talkers, the instantaneous voltage distribution may be considered as the same for all volumes when expressed as a ratio of instantaneous to rms voltage. The cumulative distribution curve of the quantity E/U, where E is the rectified instantaneous voltage and U the rms voltage, is shown by the curve $n=1$ of figure 2.

Voltage Limiting

While this curve of figure 2 is accurate for the bulk of the talkers, it changes for the high-volume talkers who overload the subset transmitters. It is also the custom to provide a certain amount of amplitude limiting in each channel by suitable circuit design of the channel terminal equipment. This limiting alters the shape of the instantaneous voltage distribution curve for a range of voltages below the maximum, the extent of the modification depending on the talker volume and the characteristics of the limiting device. Its effect on the load capacity will be considered later.

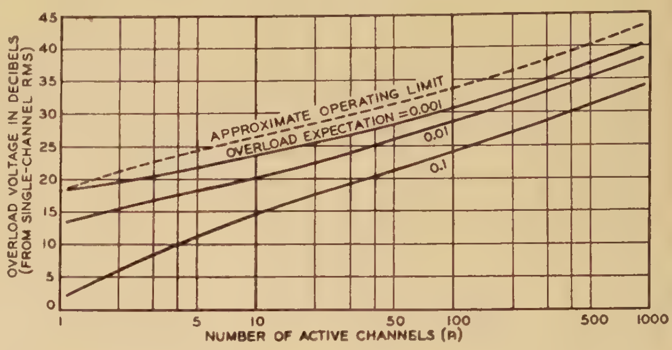
Multichannel Instantaneous Voltage Distributions

The number of variables with which it is necessary to deal makes the general load-capacity problem rather a complicated one. The analysis will be easier to follow if the effects of the different variables are taken up one at a time, thus building up a complete theory in successive steps. To do this, it is advantageous to start with a case so simplified that it rarely, if ever, occurs in ordinary practice; that is, that in which the volumes in all the channels are regulated to a common constant value, and in which the number of *active* channels is also kept constant. For this condition, it is necessary to consider only the effects of the distribution of instantaneous voltages in each channel. This distribution curve is the same for all of the channels, since all are at the same volume, but the voltage in any channel at a particular instant is entirely independent of the condition of the other channels.

Overload Expectation

The total voltage impressed on the amplifier by a number of channels at a given instant is the sum of the instantaneous voltages in the separate channels. Since disturbances will be produced in many of the channels when the applied voltage goes beyond the overload point, it will be useful to know the fraction of the time that this may be expected to occur; this fraction will be called the overload expectation and denoted by ϵ. It is important to notice that this quantity ϵ is not necessarily the fraction of the time during which the performance of the amplifier will be unsatisfactory. This might perhaps be the case for a device having an instantaneous cutoff characteristic, but for an ordinary amplifier the time constants (among other things) affect the results of overloading. The interpretation of the overload expectation will be discussed further later; consideration must be given first to how it is obtained.

Figure 3. Overload voltage for n active channels



The n-Channel Voltage Distribution

The load in each channel is applied at voice frequency to the input side of a modulator, the voice-frequency instantaneous voltage distribution being as shown by the curve $n=1$ of figure 2. The overloading of the amplifier is determined, however, by the distribution of the sum of n such voltages after each has been shifted by the modulator to the appropriate carrier frequency, one side-band being suppressed. It may be shown that if the phases of the various components of the voice-frequency input were random, the distribution of instantaneous voltage at side-band frequency would be identical with that measured at voice frequency. It is known, however, that the phases at voice frequency are not entirely random, and there may thus be differences between the two distributions. The results of a number of tests bearing upon this point indicate that any error resulting from the use of the distribution measured at voice frequency will be small for systems of few channels, and will rapidly disappear as the number of channels is increased.

Theoretically, the resultant n-channel voltage distribution can be derived from the single-channel distribution by straightforward analytical methods; in the present case, however, expression of the result in useful form is very difficult because of the form of the single-channel curve. This difficulty might be resolved by using graphical or numerical methods, as applied later to the volume-distribution curves; fortunately, the fact that the voice-frequency voltage distributions may be used throughout permitted the resultant n-channel distributions to be obtained much more easily. Since the addition of voltages from the several carrier channels does not depend materially upon the frequencies at which the channels appear in the system, the addition of n channels at voice frequency will give the desired n-channel distribution directly. M. E. Campbell effected this addition by the use of phonograph records, the n-channel distributions being determined by means of the instantaneous-voltage sampling apparatus previously mentioned.

As material for this process, 16 high-quality phonograph records were made of the outputs of commercial subsets through representative subscriber loops. Both male and female voices were used. The speech was furnished by reading magazine stories containing considerable conversational material, due precautions being taken that the volume on each

record was substantially constant throughout. A calibrating tone was cut on each record to enable it to be played at any desired volume and most of the volumes recorded were well below the point at which the transmitter began to act as a voltage limiter.

These individual records were then combined in groups of four, with all records adjusted to the same volume by means of the calibrating tones, and re-recorded. Several such 4-voice records were made; by combining them again in the same way, 16-voice records and finally 64-voice records were obtained. The instantaneous voltage distributions were measured before and after each re-recording to insure that the recording process introduced no errors. A few minor discrepancies were found, but all were small enough to be disregarded. Each single-voice record appeared several times in a 64-voice record, but since the phases of its different appearances were random, this had no appreciable effect on the resultant voltage distribution. This was verified by comparing the voltage distributions of the various possible 16-voice combinations. By this process n-channel voltage distributions were obtained for $n=1$, 4, 16, and 64.

These distributions, together with a normal curve, are shown in figure 2 in cumulative form. To show the curves conveniently to the same scale, it has been necessary to plot for each case not the distribution of E, the rectified instantaneous voltage, but that of E/U, where U is the rms voltage. The rms voltage, it will be remembered, is directly related to the equivalent volume by equation 2. The figure shows clearly the gradual transition from the single-channel distribution to the normal one for large n, and also indicates that for 64 active channels the curve is normal within the precision of the measuring apparatus. Hence, the normal distribution may justifiably be used for any value of $n>64$.

Further significance is accorded the above data by plotting the ratio of the voltage exceeded a fraction ϵ of the time to the single-channel rms voltage, as a function of the number n of active channels, for several fixed values of ϵ. From the data given, points on such curves can be obtained for $n=1$, 4, 16, 64; furthermore, the fact that the distribution for $n>64$ is normal permits drawing the asymptote for large values of n. The points read from figure 2 and replotted in this way give the full lines shown in figure 3.

In order to make practical use of these curves, it is necessary to know what value of ϵ corresponds to satisfactory performance of the amplifier. Experiments have been conducted on a number of different multichannel amplifiers, each loaded by various numbers of active channels all at the same volume. It has been found that for low enough values of ϵ, no audible disturbance is produced but that as ϵ is increased by increasing the load on the amplifier, the disturbance falling into a channel not energized increases rapidly to a large value. Two different amplifiers having the same computed load capacity may show noticeable differences in performance in this respect when subject to identical fixed loads of the type being considered, thus indicating the influence of circuit design on the value of ϵ. In general, however, the allowable values of ϵ measured for all of the amplifiers that have been tested lie in a relatively narrow band on either side of the curve for $\epsilon=0.001$. The broken curve of figure 3 represents the approximate upper limit of the observations, extrapolated parallel to the $\epsilon=0.001$ curve above $n=14$. It is possible that some amplifiers would overload even if operated in accordance with this curve, but for the great majority of amplifiers of types thus far tested the operation would be satisfactory, with perhaps a small margin.

Multichannel Peak Factor

It is useful at this point to introduce the concept of "multichannel peak factor," which is defined as the limiting ratio of the overload voltage to the rms voltage for a given number of active channels at constant volume. The ratio of the overload voltage for n active channels to the rms voltage of one active channel is given directly by the broken curve of figure 3, and the rms voltage for n channels is simply $\sqrt{n}$ times that for one channel. A simple computation then gives the multichannel peak factor. This is plotted in figure 4 as a function of the number of active channels n. The reduction in multichannel peak factor as the number of active channels increases reflects the transition from the single-channel distribution curve to the normal curve, as depicted in figure 2.

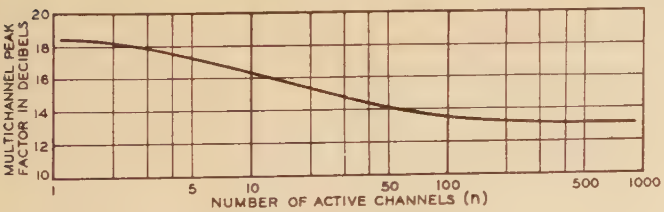


Figure 4. Multichannel peak factor for n active channels

The Distribution of Equivalent Volume

The multichannel peak factor deals only with the effects of changes in the instantaneous voltages of the channels, all other variables being fixed. It is next necessary to extend the treatment to include the effects of the other load variations that occur in practice—those in number of active channels and in channel volumes. It is important, first of all, to notice that the instantaneous-voltage variations occur very rapidly, while changes in the other two quantities are, in comparison, very slow. In the experiments described above, the loads were so fixed that the equivalent volumes could be changed only by changing the operating transmission level of the amplifier; in practical cases the amplifier transmission level is kept fixed, but the equivalent volume is constantly changing because of changes in number of active channels and in channel volumes.

The amplifier is thus loaded with a constantly changing equivalent volume but because of the great difference in the time-scales of the two classes of variations the load may be regarded as a succession of equivalent volumes, each constant for a small interval of time that nevertheless is long enough to include a representative sample of the resultant instantaneous voltage distribution. If the distribution function for equivalent volume is computed, and then corrected by the multichannel peak factor, the fraction of such intervals during which the amplifier will be unsatisfactory from the standpoint of overloading may be determined. For a particular amplifier, the operating transmission level must be so chosen that this fraction will be small enough to make any adverse effects on transmission unimportant. For systems of very many channels the proper value of this fraction is probably about one per cent. During the busiest hour, this corresponds to 36 seconds during which audible interference *may* occur and as this will be broken up into many very short intervals, the total effect should be

slight. For systems of very few channels, the equivalent volume may reach objectionably high values during these intervals and it might be necessary to make this fraction smaller than one per cent to secure good performance. For illustrative purposes, the one per cent figure will be used in what follows without implying that it may not need alteration in some cases. The methods used are applicable no matter what value is chosen for the fraction of time overloading is permitted.

Controlled Volumes

As the simplest case to which the above procedure may be applied, and one that may occasionally be of practical interest, consider a commercial system with all the channels controlled to the same volume. If there are N channels in the system, the probability that exactly n channels will be active at any given time is given by equation 1, with $\tau = 0.25$. By computing the value of $p(n)$ for all values of n, and taking the cumulative sum, the value of n which makes the sum 0.99 (or the next greater n) is readily determined. This determines the number n of active channels that is exceeded one per cent of the time. A plot of these values of n is given by the curve of figure 5, as a function of N, the number of channels in the system. For small values of N this curve has been drawn in a manner to smooth out the steps introduced because n must of necessity be an integer and when the value of n read from the curve is not an integer, the next higher integral value is to be used. It is of interest to compare this curve with the two straight lines of the figure. The lower straight line represents the asymptote for sufficiently large N and the upper straight line is for the condition where all channels are active simultaneously ($n = N$).

The average power for n channels is n times that of one channel, and the equivalent volume expressed in decibels is $10 \log_{10} n$ above that in one channel. The equivalent volume may thus be computed as a function of n, and by means of figure 5, as a function of N. Curve A of figure 6 shows the values of equivalent volume so determined as a function of N, the number of channels in the system; it applies specifically to the case where the volume of each of the active channels is controlled so as to be 12.1 decibels below reference volume. The choice of this particular volume is purely arbitrary, but it corresponds to the average power of the single-talker volume distribution.

The equivalent volumes given by curve A of figure 6 are a measure of the average power of the N channels, as computed by means of equation 2. To determine the required instantaneous load capacity of the system, the average power must be corrected by the multichannel peak factor which is read directly from figure 4, using for the number of active channels the values read from figure 5.

For design purposes, it is more convenient to use the rms power of the single-frequency test tone whose peak value represents the instantaneous load capacity. As the ratio of the peak to rms power of a single-frequency tone is three decibels, this test power is obtained by subtracting three decibels from the instantaneous load capacity. This required test-tone capacity is plotted as a function of N in curve A of figure 7, which gives the output capacity required for an N-channel system with volume control as specified above.

Uncontrolled Volumes

For systems in which volume control is not used, the application of this procedure becomes more involved. To study this more general case, it is convenient first to interchange the conditions of the preceding section, letting the number of active channels be fixed at any value n and examining how the distribution curve of equivalent volume may be obtained for this fixed number of channels. The relation between volume and average speech power given in equation 2 may be rewritten for this case in the form

$$V_i = 10 \log_{10} \frac{W_i}{W_0} \text{ decibels}$$

where $W_0 = 1.66$ milliwatts, W_i is the average speech power in milliwatts, and V_i is the volume in decibels for any one of the active channels, all at a point of zero transmission level.

Likewise, the relation between equivalent volume and average speech power for n active channels is given by the expression

$$V = n\text{-channel equivalent volume} = 10 \log_{10} \frac{\sum_1^n W_i}{W_0} \text{ decibels}$$

Since the distribution of the channel volumes V_i is known and the volumes of the various channels are independent, the straightforward procedure to obtain the distribution of the n-channel equivalent volume V would involve the following steps: (1) the obtaining of the distribution function of W_i by a transformation of that of V_i; (2) the calculation of the distribution function for the quantity $Y(n) = \sum_1^n W_i$; (3) the transformation of

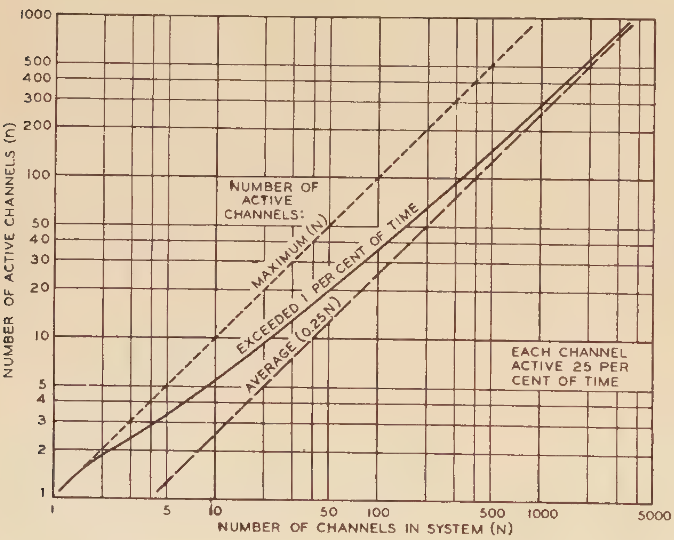
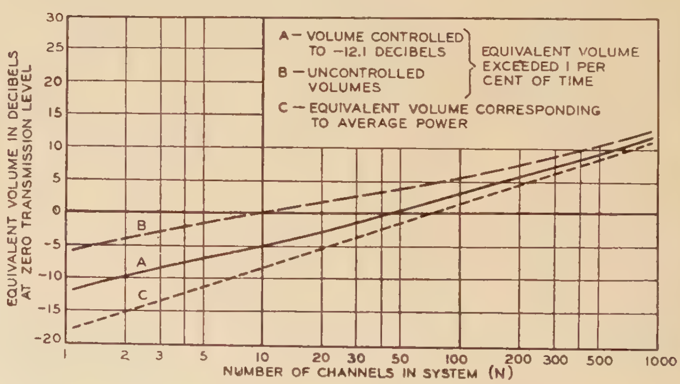


Figure 5 (left). Number of active channels as a function of the number of channels in the system

Figure 6 (below). Equivalent volume for systems of N channels



the $Y(n)$ distribution to that of V by inverting the process used in step 1.

The difficulties in this process are all in the second step, where, having given $p_1(W)$, the distribution of average powers for a single channel, it is required to obtain $p_n(Y)$, the distribution for n active channels, with Y defined in terms of W by the relation given immediately above. The formal solution requires the evaluation of integrals of the following type:

$$p_n(Y)=\int_0^Y p_{n-k}(W)p_k(Y-W)dW$$

By successive calculation of such integrals for $n=2, 4, 8$ . . ., taking k each time equal to $n/2$, the required distributions may be obtained for the necessary range of values of n.

As in the case of the instantaneous-voltage distributions, it has not proved feasible to perform the integrations analytically. It was necessary to resort to numerical evaluation of these integrals; by combining the transformations in steps 1 and 3 with the process of evaluating the integral, the process was somewhat shortened. In this way equivalent volume distributions have been obtained for $n=2, 4, 8, 16$ . . .; needed points on the distribution curves for intermediate values of n are obtainable by interpolation.

The accuracy of such a process depends upon the number of division points used in the numerical integration and this as a practical matter must be kept fairly small. When the process must be repeated many times, the errors introduced at each step may accumulate and lead to inaccuracies for large n. It is thus desirable to have some control over the accuracy other than by repeating the calculation with a larger number of division points. This is provided by calculating the moments of $p_n(Y)$ from those of $p_1(W)$ without the use of numerical integration.

The moments S_k of $p_1(W)$ are defined by

$$S_k=\int_0^\infty W^k p_1(W)dW$$

and the moments $T_k^{(n)}$ of $p_n(Y)$ similarly. By the use of the semi-invariants of Thiele,* it may be shown that

$$T_1^{(n)}=nS_1$$

$$T_2^{(n)}=nS_2+n(n-1)S_1^2, \text{ etc.}$$

By comparing the moments of the distributions obtained by numerical integration with those calculated in this way, and making occasional minor alterations in the curves to bring the first and second moments into agreement, assurance was obtained that all the distributions used are reasonably accurate, with no accumulation of error as n becomes large.

Examples of the cumulative distribution curves of equivalent volume for 1, 4, 16, and 64 active channels are given in figure 8. The decrease in standard deviation which occurs as n increases is of interest for it indicates how the fluctuations in load due to talker volume variations are reduced by combining a large number of channels in one system.

Having now n-channel equivalent volume curves for a range of values of n, the resultant equivalent volume curves may be calculated when the restriction to a fixed number n of active channels is removed. Let $p_n(V)$ denote the probability that, with n channels active, the equivalent volume lies between V and $V+dV$ and let $p(n)$ denote the probability that just n channels *will* be active. Then the total probability that the equivalent volume will be between V and $V+dV$ is given, for an N-channel system, by

$$p(V)=p(1)p_1(V)+p(2)p_2(V)+\dots+p(N)p_N(V)$$

The $p_n(V)$ are given by equivalent volume curves such as those in figure 8 and the $p(n)$ by equation 1. Examples of curves thus computed are given in figure 9, which shows the equivalent volume distributions at a point of zero transmission level for 3, 12, and 240 channel systems. The equivalent volume that is exceeded one per cent of the time, read from such curves, is plotted as curve B of figure 6.

This curve gives, for any number of channels having uncontrolled volumes, the equivalent volume which will be exceeded just one per cent of the busy hour. To obtain the necessary load capacity, this must be corrected for the multichannel peak factor. In the controlled-volume case, for a given number N of channels in the system, there was no difficulty in deciding the value of n, the number of simultaneously active channels, for which the multichannel peak factor should be taken. Now, however, there is no unique relation between equivalent volume and the number n; in addition, the multichannel peak factors were measured with all n channels at the same volume, which represents a condition rarely holding on a system without volume control. It is apparent, however, that in the majority of cases in which the equivalent volume approaches values on curve B of figure 6, the number of simultaneously active channels will be greater than the average number N_T of active channels. Since the multichannel peak factor decreases as n increases, the peak factors for $n=N_T$ active channels

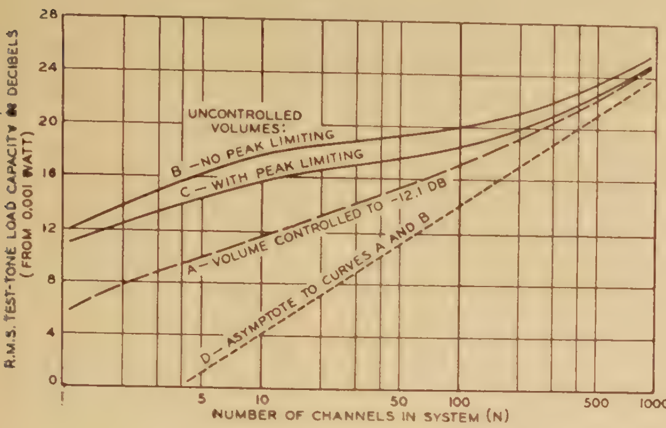


Figure 7. Load capacity for systems of N channels

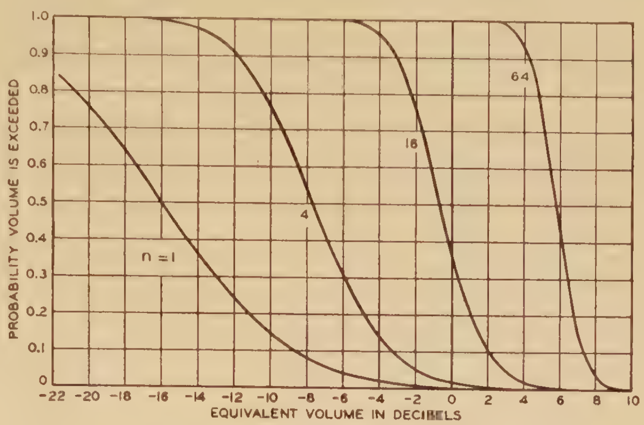


Figure 8. Equivalent volume distributions for n active channels

* T. N. Thiele, "The Theory of Observations," 1903; reprinted in *Annals of Mathematical Statistics*, volume 2, 1931. See especially sections 22, 29.

may be safely used. A more detailed analysis, feasible only for very small systems but avoiding the use of this approximation, shows that its effect is small and tends to give load capacities slightly higher than actually required, but the difference diminishes rapidly as the size of the system is increased.

For the uncontrolled volume condition, therefore, the multichannel peak factors are read from figure 5 for values of $n = N_T$. They are added to the equivalent volumes obtained from curve *B* of figure 6, and reduced to single-frequency power as previously described for the volume-controlled case. Curve *B* of figure 7 is obtained in this manner and shows the load capacity required in an amplifier for an *N*-channel system in which the volumes of each channel are distributed in accordance with curve *A* of figure 1. The load capacity which is approached asymptotically as *N* increases indefinitely is represented by curve *D* of figure 7.

The load capacities given by figure 7 are valid only for systems for which the basic single-channel data apply. As these may not hold in specific cases, and may be subject to modification in the future, estimates of the effects of small changes in these data are useful. These effects cannot be described simply for moderate numbers of channels but for large numbers of channels the effects are readily estimated from the change in the location of the asymptote shown on figure 7. The equation of this asymptote is as follows:

$$L = 10 \log_{10} N_T + (V_0 + 0.115\sigma^2) + MPF + P_0 - 3 \text{ decibels}$$

where

L = test-tone load capacity
MPF = asymptotic multichannel peak factor
P_0 = long average power of a reference volume talker in decibels above 0.001 watt

The other quantities are as defined before.

Peak-Voltage Limiting

The curves referred to in the preceding discussion have so far neglected the effects of peak-voltage limiting in the transmitters and in the channel terminal equipment. Fundamentally, the effect of such limiting is to modify the distribution of instantaneous voltages in the individual channels. The extent of the modification, however, depends on the volume. For single-channel systems it is obvious that the improvement in load capacity due to limiting will be substantially equal to the reduction in the maximum peak voltage. For a large number of channels the improvement will approach the reduction in the rms voltage per channel. An approximate method of accounting for these complicated reactions is to consider that peak-voltage limiting modifies the upper end of the single-channel volume distribution. Strictly the amount of such modification is a function of the number of channels as well as of the characteristics of the limiters. Curve *B* of figure 1 represents a compromise between the different effects which is believed to give reasonably accurate results for both small and large numbers of channels for the limiting characteristic of present terminals.

With the talker volume distribution modified in accordance with curve *B* of figure 1, computations of the load capacity with voltage limiting present may be made in a manner identical with that previously described. Curve *C* of figure 7 shows the results obtained for this amount of limiting.

All of the load capacity curves of figure 7 are based on the equivalent volume which would be exceeded one per cent of the time, irrespective of the number of channels in the system. Where voltage limiting is used, it appears reasonable to consider this percentage as fixed because the action of the limiters serves to restrict the range of voltages above the overload point, thus reducing the severity of any overloading effects. When there is no limiting, and particularly for a small number of channels, the range of overloading voltage is not so restricted and overloading effects may become undesirably severe during the one per cent of time when the overload voltage is exceeded. If voltage limiting is not provided in some form, it may be important to reduce the percentage of time during which overloading may occur for small numbers of channels. This is a matter to be determined by experience and, if necessary, would require modification of curve *B* of figure 7 in the direction of requiring more load capacity for a small number of channels, thus increasing the spread between curves *B* and *C*.

Operating Margins, Etc.

The curves which have been given for output capacity versus number of channels apply to a single amplifier, or to a system in which all amplifiers are identical and work at the same output level without appreciable impairment of over-all performance. In practice, the number of amplifiers in tandem n a long system may be very large and problems of equalization and regulation may make it difficult to maintain exactly the same level conditions at all amplifiers. In addition, aging of tubes, and other effects will introduce some impairment. It is important, therefore, to allow a margin for these effects in the design of an amplifier for a multichannel system. The proper margin is essentially a matter of system design and it is often economical to build a liberal margin into the amplifiers in order to allow greater latitude and economy in the design of equalizing and regulating arrangements.

In addition to the speech loads, there are also impressed on the amplifiers various signaling and pilot frequencies, carrier leaks, etc. It is not always possible in practice to make these negligibly small and the load-capacity requirements must be corrected to allow for their presence. Multichannel telephone systems are also required to transmit other types of communication circuits, such as program channels and voice-frequency telegraph systems, superposed on one or more telephone channels. Modifications of the methods applied to speech loads may readily be made to determine the effect of these on the amplifier load capacity.

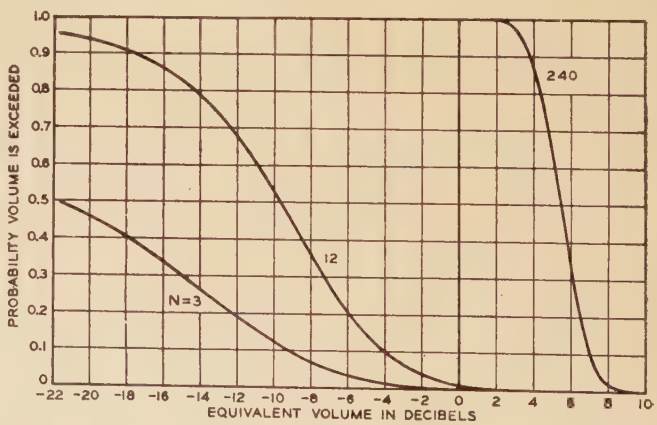


Figure 9. Equivalent volume distributions for systems of N channels

An Unstable Nonlinear Circuit

CLAUDE M. SUMMERS
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An iron-core reactor in parallel with a capacitor in a series circuit with some kind of impedance will exhibit unstable characteristics under certain conditions. A change in one or more of the circuit parameters will cause the current or voltage associated with some element of the circuit to change suddenly from one stable value to another. Between these two conditions no value of current or voltage will satisfy all of the elements of the circuit simultaneously.

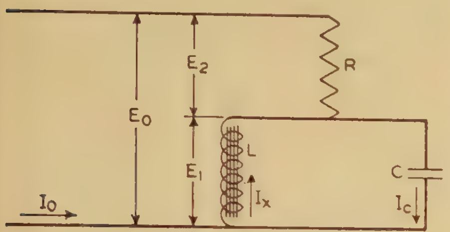

Figure 1. The parallel type of nonlinear circuit

The instability of certain types of circuits has been encountered in the past, especially on three-phase metering circuits. In general this is an undesirable condition, but there are several methods by which some practical use may be made of the unstable characteristics of the parallel reactor and capacitor circuit.

An accurate mathematical analysis of the circuit is very difficult because the exact equations of magnetic phenomena, and of the current and voltage wave forms, are quite complicated. Only a simplified theory is considered, and the discussion is based largely on the data taken on typical test circuits.

Circuit Characteristics

A circuit similar to figure 1 where the series impedance consists of pure resistance is the most simple form of the circuit. The measured characteristics of the reactor and capacitor as well as their combined volt-ampere curve are shown in figure 2. As the series resistance varies from a maximum to a minimum and returned to its highest value, at a constant line voltage, the voltage common to the reactor and capacitor follows the curve in figure 3. With decreasing values of resistance the voltage E_1 follows the curve VAX to the critical point X. A further incremental decrease in resistance causes the voltage suddenly to change from 49 volts to 102 volts and the line current likewise suddenly changes from 0.60 amperes to 0.14 amperes. If the resistance is further decreased, the voltage will continue along the curve YN, but if the resistance is increased the voltage will proceed along the curve NYZ to a second critical point Z where there is again a sudden readjustment of voltage—this time a collapse from 96 volts to 34 volts, and the current changes suddenly from 0.21 to 0.50 ampere.

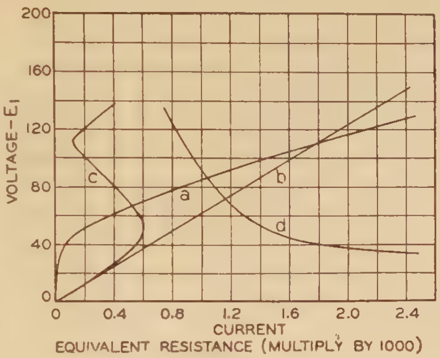

Figure 2. Characteristic curves of parallel branch of the nonlinear circuit, obtained from measurements

a—Reactor volt-ampere curve
b—Capacitor volt-ampere curve
c—Volt-ampere curve of combined reactor and capacitor
d—Equivalent resistance of reactor

Referring again to figure 3, the stable conditions along that portion of the curve VAX is called a substable state and is characterized by relatively low flux density in the reactor, good wave forms of current and voltage in all elements of the circuit, and by the line current leading the reactor voltage. After the circuit passes through the unstable period, stable conditions again prevail along the curve NYZ, which is called a hyperstable state. It has associated with it a relatively high flux density in the reactor, distorted wave forms, and in general the line current lags the reactor voltage.

Thus, there is a hysteresis-loop effect where the two critical points do not coincide. It has been found that the area within this hysteresis loop can be varied by changing one or more of several factors such as line voltage, the relation between the reactor and capacitor volt-ampere curves, or the equivalent resistance of the parallel circuit. The effect of varying the line voltage is shown in the group of curves in figure 4.

It has been observed that the unstable phenomena may be produced under certain conditions by a variation in any one or more of the quantities such as reactance, capacitance, series impedance, line voltages, or frequency. Thus, in the circuit considered above, figure 4 shows that instability will be encountered between 115 and 125 volts if the series resistance is fixed at 170 ohms. However, figure 4 also shows that the circuit will not become unstable for a variation in resistance or line voltage providing the latter never exceeds 100 volts. It is evident, therefore, that there are some factors that govern the instability of the circuit, and these can be understood more easily from a simple graphical analysis of the above circuit.

Circuit Theory

Figure 2 gives sufficient data to permit an approximate calculation of the instability curves as illustrated by an example in the appendix. The calculated curve in figure 5 indicates that the curve of series impedance has a maximum and minimum point, and that these agree reasonably well with the critical points of figure 3 for a line voltage of 125 volts. No correction was made for the distorted

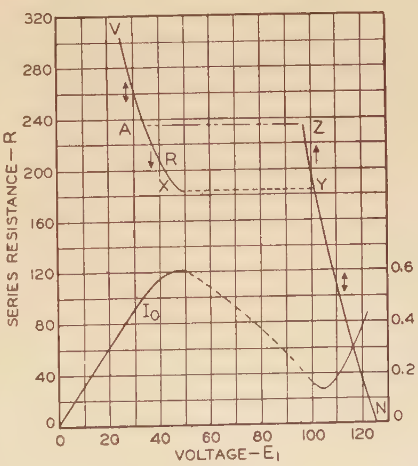

Figure 3. Instability curve for a line voltage of 125 volts

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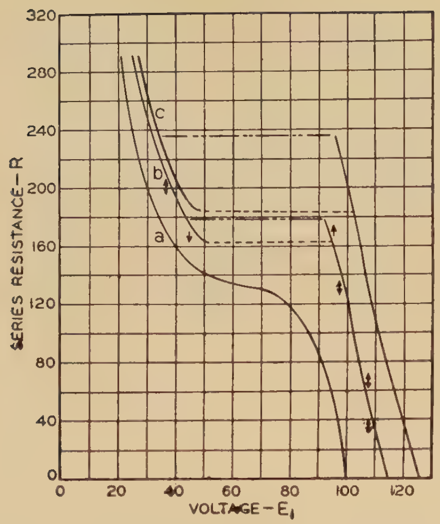

Figure 4. Effect of line voltage on instability

a—Line voltage 100 volts
b—Line voltage 115 volts
c—Line voltage 125 volts

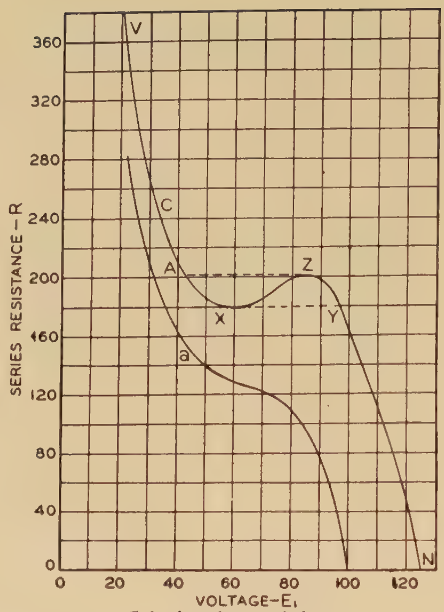

Figure 5. Calculated instability curves at line voltages of 100 volts (a) and 125 volts (c)

waves associated with the hyperstable condition, hence the greater discrepancy between the maximum and the critical point *Z*. The impedance curve for a line voltage of 100 volts does not contain maximum and minimum points; thus it may be concluded that the primary requisite for instability is that there must be such a relation between the various elements of the circuit that there will be a maximum and minimum point in the curve of series impedance plotted against the voltage common to the reactor and capacitor. Mathematically, the first derivative of an equation of *R* in terms of E_1 will show the presence of instability and the location of the critical points. If a different relation between the reactor and capacitor volt-ampere curves is chosen, the maximum and minimum points will occur at different values of series resistance and a different value of line voltage must be maintained before instability will occur. Thus, the reactance, capacitance, and their equivalent resistance, the series impedance, and the line voltage must be correlated if instability is to be avoided or deliberately produced. There are three probable fields where the characteristics of instability deliberately produced may have some useful application. These are phase shifting, energy transformation, and circuit control.

Utilization of Instability—Phase Shifting

If the circuit represented by the curves in figure 2 is applied to a line voltage 160 volts or higher, the highest value of E_1 in the substable range is about 55 volts. The capacitor current, curve *b*, is substantially greater than the reactor current at this point hence the line current, curve *c*, is leading the line voltage. The lowest value of E_1 in the hyperstable state may be 120 volts where current in the reactor is now greater than that in the capacitor and the line current lags the line voltage.

Thus, the line current in a nonlinear circuit, designed so that the hyperstable state will be well above the intersection of the reactor and capacitor volt-ampere curves, will shift from a large leading angle to a large lagging angle when passing into the hyperstable state. A reversing motor may be made by inserting this nonlinear circuit in series with one winding of a split-phase motor as in figure 6. A change in line voltage, or any other factor which will cause a shift from one stable state to the other, will cause a reversal of rotation. In fact, if the impedance of the series winding changes sufficiently with speed, the motor will continuously oscillate, first in one direction, then in the other. The number of revolutions in each direction depends on the value of line voltage, and at one value of voltage the net revolutions is zero. A reduction of one per cent or more may cause a net gain of revolutions in one direction while an increase in line voltage will produce a net gain in the other direction.

Figure 7 is an oscillogram of line current and reactor voltage for the substable and hyperstable states. The current leads the voltage by approximately 75 degrees and three cycles later it lags by about 60 degrees.

Energy Conversion

A nonlinear circuit of a little different construction from those previously mentioned is shown in figure 8. The reactor not only acts as an autotransformer, but it acts as a solenoid to raise a plunger. Let the line voltage, frequency, series impedance, and capacitance remain con-

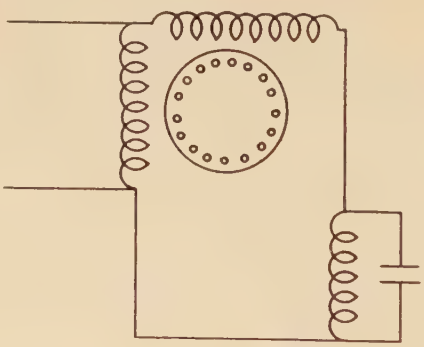
Figure 6. (above). Split-phase motor with unstable circuit

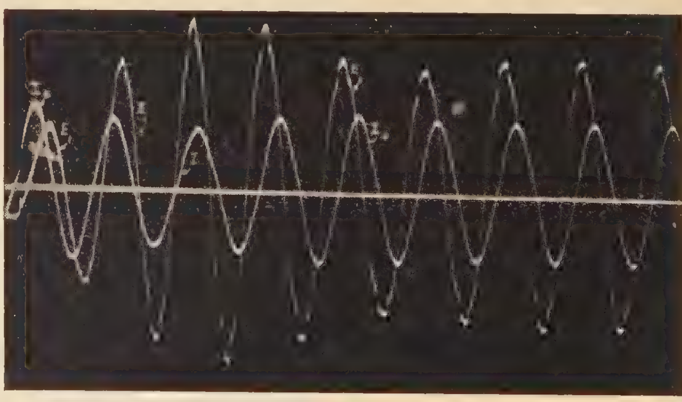
Figure 7. Oscillogram of transition from substable state (on left) to hyperstable state (on right)

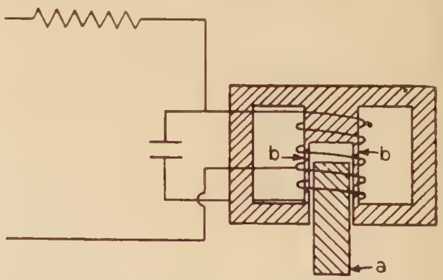

Figure 8. Arrangement of nonlinear circuit to produce reciprocating motion

a—Movable core *b*—Saturated section

stant and assume that the reactor operates in the substable state when the plunger is in the solenoid. The flux density in the reactor is low and the majority of the flux passes through the saturated section of steel, b. The small amount of flux passing through the plunger does not create a sufficient magnetic pull on the plunger to hold it against gravity or some other external force. Consequently, an external force will pull the plunger out of the solenoid and in doing so, the equivalent reactance of the circuit is changed sufficiently to cause the circuit to pass into the hyperstable state. The high voltage across the reactor then produces a sufficiently high flux to overcome the external force and the plunger moves into the solenoid. The forward motion of the plunger, however, causes the circuit to return to the substable condition, the attraction is released, and the external force again removes the plunger. Reciprocating motion is thereby produced and maintained as long as the motion of the plunger is capable of causing a transfer from one stable state to the other. The action is more easily understood from the hysteresis-loop characteristic curves in figure 9 where plunger displacement is plotted against magnetizing current in the reactor. This curve indicates a large difference between the attractive force for the inward and outward stroke.

If two similar reactors are connected by a common core as in figure 10, a continuously reciprocating system is obtained with power delivered during each stroke. In this circuit each reactor and capacitor group acts as a series impedance for the other. A reciprocating air compressor with a laminated iron core mounted on each end of the piston was inserted between two units. A pressure of 75 pounds per square inch was established in approximately two minutes in a container having a volume of 0.1 cubic foot, with the circuit oscillating at 240 strokes per minute. When the maximum pressure was obtained, the reciprocating motion ceased because the back pressure on the piston was equal to the magnetic attraction on the plunger. The power consumed under the stalled condition, was about one-fourth of its value when the unit was in motion. When the air pressure was reduced to a value sufficiently low for the attractive force to overcome this pressure and the static friction, the pump automatically started.

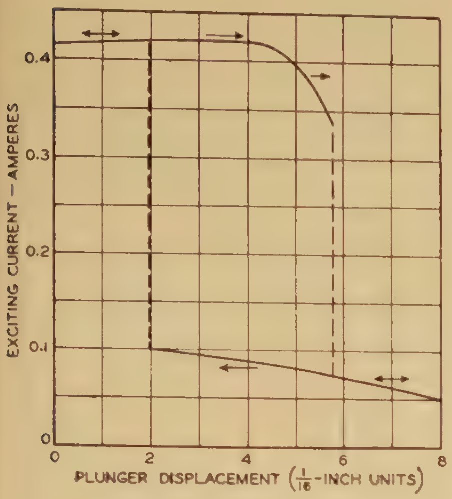

Figure 9 (left). Unidirectional pull on plunger of unstable circuit

Plunger moving into solenoid ⟶
Plunger moving out of solenoid ⟵

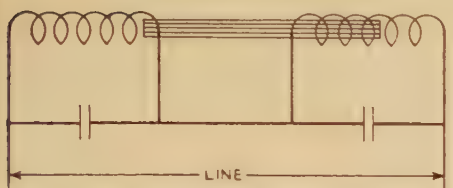

Figure 10. Circuit for producing double-acting reciprocating motion

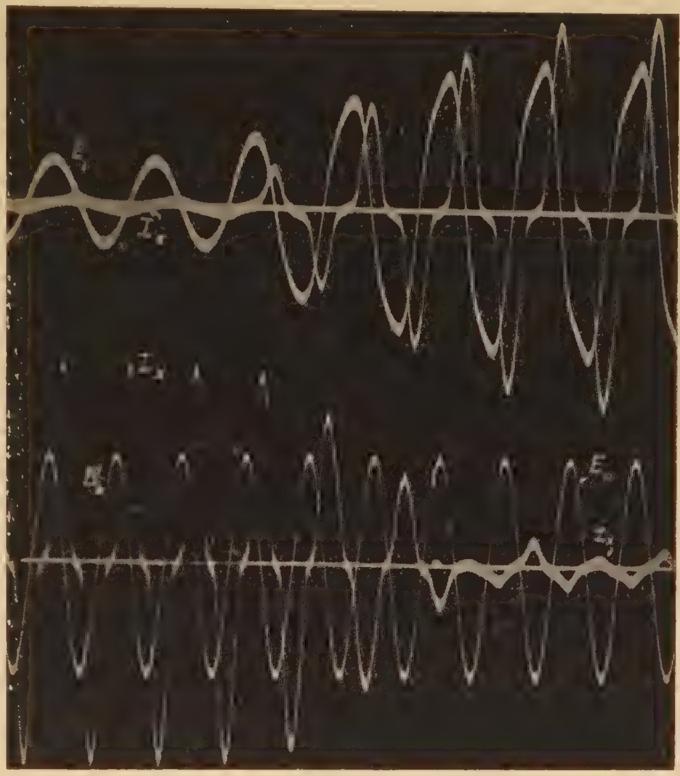

Figure 11. Oscillogram showing change in exciting current during motion of plunger

Top—Plunger moving out of solenoid

Bottom—Plunger moving into solenoid

E_0 = line voltage, E_1 = reactor voltage, I_x = reactor current

The frequency of the supply circuit affects the operation of reciprocating motion to some extent because it tends to change the period of oscillation of the plunger, and the area of hysteresis loop. For the circuit on which the tests were made, however, the frequency could be varied 20 cycles or more and the line voltage could be varied over a range of 100 per cent without causing the reciprocating motion to stop. The frequency of reciprocating motion depends not only upon the mechanical inertia but upon the electrical constants of the circuit. A change in capacitance or equivalent resistance in parallel with a nonlinear reactor will change the period of reciprocation within certain limits.

Oscillograms in figure 11 show the rapid rate change of exciting current in the reactor when the core is suddenly withdrawn, and inserted.

A circuit similar to figure 8 may be used for electric bells, gongs, or signals without electrical contacts. The transformer A shown in series with the reactor and capacitor B in figure 12 is used instead of the ordinary bell transformer. The internal impedance of this transformer on open circuit is so high that instability cannot occur in the nonlinear circuit. When the secondary of the transformer is closed, however, the series impedance is reduced to a value which establishes reciprocating or vibrating mechanical motion.

Circuit Control

The nonlinear circuit may find many applications in controlling circuits but only a temperature control will be mentioned as an illustration.

The circuit shown in figure 8 may be a relay circuit in which a nonlinear re-

actor is used as the relay itself, that is, the plunger may carry the relay or circuit-breaker contacts. If the area of the plunger and saturated section are properly proportioned a continuous attractive force may be maintained instead of the reciprocating action. In other words, the motion of the core would not cause the system to change from one stable state into the other; but instability could be controlled by a variation in line voltage, series impedance, or some other suitable factor. A thermostat placed across the series resistance of the nonlinear reactor could control a power circuit without intermediate contactors or amplifiers. The important factor is that a small variation in the series impedance is amplified to produce a large and sudden variation in the voltage across the reactor which in turn influences the pull on the plunger.

A temperature-control circuit may be arranged as in figure 13 in which two series resistors have equal and opposite temperature coefficients of resistance. Tests on constant line voltage and frequency indicate that an increase of 0.4 per cent in one resistor and a corresponding decrease in the other resistor will cause the plunger to shift from the one reactor into the other. Thus, a temperature-control system could be operated without a thermostat or contact and would be relatively sensitive to temperature changes providing the line voltage and frequency remained constant. Two metals having practically equal and op-

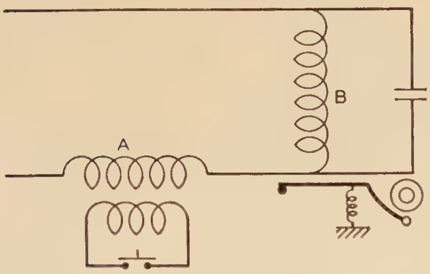

Figure 12. Unstable circuit for an electric bell without contacts

posite temperature coefficients of resistance are titanium and zinc. The temperature sensitivity at constant line voltage and frequency in such a system would depend upon the value of temperature coefficient necessary to produce the required change in resistance. The 0.4 per cent change mentioned above would require a temperature change of less than two degrees centigrade to shift the plunger from one coil to the other if the series resistors were made of titanium and zinc. The effect of the line voltage and frequency depends upon the actual change occurring in series impedance. For example, if the temperature control system is set up as in figure 13 with a thermostat added as shown by the dotted lines, which short-circuits as much as 20 per cent of one resistor or the other; the effect of line voltage and frequency becomes negligible. An actual circuit operated

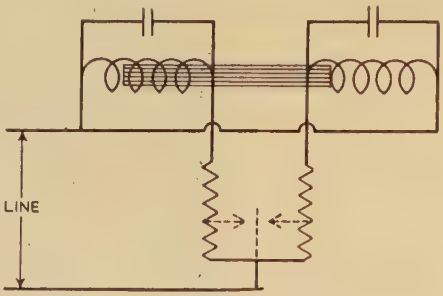

Figure 13. Temperature control circuit

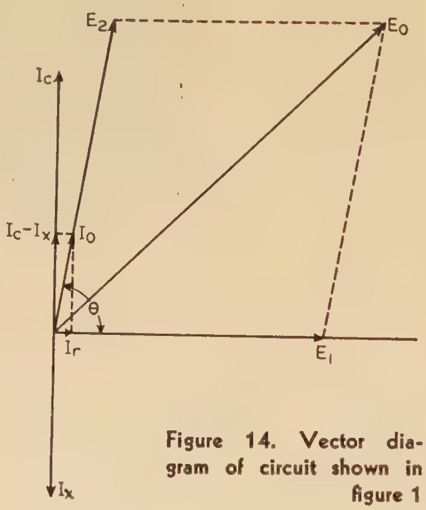

Figure 14. Vector diagram of circuit shown in figure 1

satisfactorily over a 10-cycle change in frequency and a 20-volt variation in line voltage.

Summary

An instability curve of series impedance versus voltage common to the parallel branch of the circuit as in figure 1 can be calculated approximately. If this curve contains maximum and minimum points, the circuit will have two states of stability with an intermediate unstable range. Some practical use of this phenomenon has been suggested for circuit control and energy conversion. The circuit which produces reciprocating motion has not been completely analyzed, hence the optimum operating conditions cannot be stated until further knowledge is obtained.

Appendix

Any point on the instability curve can be calculated in figure 5 as in the following example which corresponds to a value of E_1 of 80 volts. From figure 2 we find that the measured line current I_0 is 0.42 ampere and that the equivalent resistance R_e is 1,090 ohms. The equivalent impedance is

$$Z_e = \frac{E_1}{I_0} = \frac{80}{0.42} = 190.5 \text{ ohms} \tag{1}$$

The phase angle between the line current and reactor voltage therefore is, from figure 14,

$$\cos\theta = \frac{Z_e}{R_e} = \frac{190.5}{1{,}090} = 0.175 \tag{2}$$

Since E_2 is a resistance voltage drop it is in phase with I_0, and the relation between E_1, E_2, and E_0 is, from figure 14,

$$E_1^2 + E_2^2 + 2E_1E_2 \cos\theta = E_0^2 \tag{3}$$

Assume a line voltage of 125 volts. Then

$$(80)^2 + E_2^2 + 28E_2 = (125)^2 \tag{4}$$

from which

$$E_2 = 83 \text{ volts} \tag{5}$$

Then

$$R = \frac{83}{0.42} = 197.5 \text{ ohms} \tag{6}$$

When curves a, b, and d in figure 2 are available, the resultant current curve c can be calculated approximately as follows:

The component of current due to the equivalent resistance is

$$I_r = \frac{E_1}{R_e} \tag{7}$$

and

$$I_0 = \sqrt{(I_c - I_x)^2 + (I_r)^2} \tag{8}$$

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Theory and Design of NEMA Resistors for Motor Starting and Speed Control

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Synopsis: The National Electrical Manufacturers' Association classification of resistors for motor starting and speed control specifies the initial current peaks and the duty cycle for which the resistor must be designed. The nature of the load driven by the motor decides the valley current at which succeeding resistor steps must be switched in starting, and consequently the number of steps in the resistor, and points in the controller. The rms current, and the time each step is in the circuit, taken in conjunction with the cyclic current-carrying capacity of individual resistor elements, determines the selection of the elements on the basis of their continuous-current rating. It is usual to assume an rms current of 125 per cent, and switching at equal time intervals. However, in this paper, formulas are developed for more accurately calculating these values, and the formulas and necessary constants are tabulated. Consideration is given to d-c shunt and series-connected motors, and to wound-rotor a-c induction motors. Resistors for regulating duty are also discussed.

THE performance of any motor controller depends primarily upon the accuracy of the resistor design. A knowledge of the fundamental relations involved, and the theoretical basis and practical methods of resistor design are necessary to a clear understanding of motor control.

Resistor design has been simplified, and to some degree standardized, by a standard classification system. Such a system was adopted in 1917 by the Electric Power Club. The club was later merged into the National Electrical Manufacturers' Association, and the classification scheme became known alternatively as the American Engineering Standard or the NEMA standard system.

It was first based upon a four-minute duty cycle, but a few years ago was modified to conform more nearly with actual duty cycles most common in practice. The various classes are indicated by numbers. As originally used there were two figures in the class numbers, the first representing the duty cycle and the second the initial or peak value of the starting current. When the classification was revised, inasmuch as it was necessary to change the meaning of some of the figures, the number of digits was increased to three by the addition of the figure "1" before the two significant figures, to indicate the new classification.

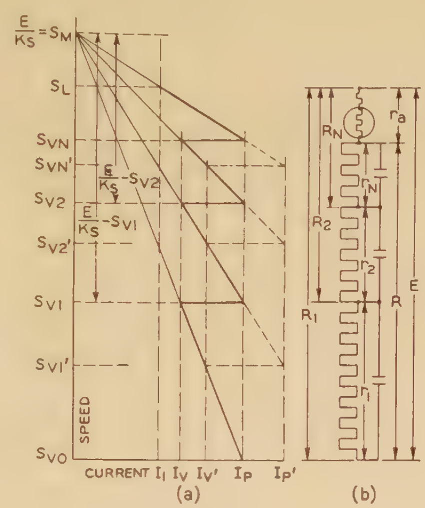

Figure 1

(a)—D-c motor speed-current relations with a NEMA starting resistor

(b)—Circuit connections

This classification, together with approximate starting torque, is given in table I.

Shunt-Wound D-C Motors—Total Resistance Value

On the first point of the controller, all of the resistance is in the circuit, the current rises toward a peak value determined by Ohm's law. However, as the motor starts, a counter electromotive force is developed in the armature which is proportional to the speed, and the current decreases toward a value which is just sufficient to develop the torque necessary to carry the mechanical load. The applied voltage, E, is at any instant exactly balanced by the sum of the resistance drop, ir, and the counter electromotive force so that, in a shunt-wound motor,

$$E = ir + K_s s \tag{1}$$

in which s is the speed, and the constant K_s may be evaluated by substituting for the other symbols the motor rated voltage, current, and speed, and the armature and lead resistance.

For current equal to zero, the second term vanishes, and the current-speed curves converge to the maximum theoretical speed, E/K_s, for all values of r, as shown in figure 1.

Now let it be assumed that the controller is arranged to cut out each succeeding step of resistance at the instant the current decreases to a value I_v, and that the resistance steps are so proportioned that the current peaks are each equal to I_p, on the successive steps. Then the current-speed curves take the form shown by the heavy lines of figure 1*a*. As the total resistance takes the successive values, $R_1, R_2 \ldots R_n \ldots r_a$, at the successive instants of switching, the currents have become I_v, and the speeds $S_{v1}, S_{v2}, S_{v3}, \ldots$ etc. For any step, n,

$$E/K_s = I_v R_n / K_s + S_{vn} \tag{2}$$

From similar triangles

$$\frac{I_p}{I_v} = \frac{E/K_s - S_{vn}}{E/K_s - S_{v(n+1)}} = \frac{R_n}{R_{(n+1)}} \tag{3}$$

Let

$$X = I_p / I_v \tag{4}$$

Then $R_n = XR_{(n+1)}$, and the total resistance

$$R_1 = E/I_p = XR_2 = X^2 R_3 = \ldots X^{(N-1)} R_N = X^N r_a \tag{5}$$

and

$$R_N = X r_a \tag{6}$$

Let $r_1, r_2, r_3 \ldots r_N$ be the successive values of the individual resistance sections, numbered from the line terminal, as indicated in figure 1*b*, and let it be assumed that the resistance of armature and leads is expressed as a fraction, Z, of line voltage divided by rated motor current; that is:

$$r_a = ZE/I \tag{7}$$

It is standard practice to assume values for Z except in the case of very large motors, inasmuch as even quite a large percentage error will have little effect except in the current peak on the last point of the controller. For most motors 0.1 is a fair approximation.

Let the ratio of the current peaks to rated current be represented by Y. That is:

$$I_p = YI \tag{8}$$

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The values of Y for the various NEMA classes are indicated in the first column of table I, and are repeated in table II.

Also, let the external resistance, R_1-r_a, be represented by R. Then

$$R=UE/I \tag{9}$$

Here, U, defined by the equation, is, for $Z=0.1$.

$$U=1/Y-0.1 \tag{10}$$

It is the constant which when multiplied by the ratio of voltage to normal current gives the total ohmic value of the resistance for a particular application and class number.

The last step in the resistor is given by

$$r_N=R_N-r_a=R(X-1)Z/U$$
$$=R(X-1)/10U=C_rR \tag{11}$$

C_r is a constant defined by the equation.

The resistance of any other step, n, is

$$r_n=Xr_{(n+1)} \tag{12}$$

From equation 5 the number of steps in the resistor should be

$$N=\log(10/Y)/\log X \tag{13}$$

Inasmuch as N must be a whole number, this equation is necessarily used to determine X for assumed values of N, and the valley current can only approximate a desired value. *For the current peaks to be equal, and performance to be in accordance with the resistor design, the accelerating relays should be set to operate at*

$$I_v=IY/X \tag{14}$$

Values of C_r, U, and X are given in table II.

Accelerating Time

In order to determine the current-carrying capacities necessary for the successive resistor steps, it is necessary first to consider the variations of the motor speed with time. It is to be noted that the following assumptions are made.

1. Torque of the load is constant and less than the torque developed by the motor when carrying current equal to I_v.
2. The field excitation is constant.
3. The effect of inductance in delaying the rise of current, and hence, upon the peak value, is neglected.

The motor speed in radians per second is $2\pi s/60$, or $0.105s$.

The instantaneous torque is proportional to the instantaneous armature current, which in turn is given in terms of voltage and speed by equation 1. This torque is balanced by the sum of the torque of the motor load and the torque of acceleration, that is

$$K_t(E-K_ss)/r=0.105J\,ds/dt+L \tag{15}$$

where L is the torque of the load, r is the total circuit resistance at the particular time, K_t is a constant, which may be evaluated when the rate of acceleration ds/dt is zero, and $E-K_ss$ is equal to rI_L, the resistance drop at the current I_L required to carry the load. This gives L/K_t equal to I_L.

Hence equation 15 may be put in the form

$$\frac{ds}{dt}+\frac{K_tK_ss}{0.105Jr}=\frac{K_t}{0.105J}\left(\frac{E}{r}-I_L\right) \tag{16}$$

This is a linear differential equation the solution of which is

$$s=\left(\frac{E}{r}-I_L\right)r/K_s+C\epsilon^{-K_tK_st/0.105Jr} \tag{17}$$

t being time, ϵ being the base of the Naperian logarithms, and C a constant of integration, which may be evaluated by taking $t=0$ at $s=S_{v(n-1)}$ for the nth resistor step, when $r=R_n$, so that in

$$s=\left(\frac{E}{R_n}-I_L\right)\left[\frac{R_n}{K_s}+S_{v(n-1)}-\left(\frac{E}{R_n}-I_L\right)\frac{R_n}{K_s}\right]\epsilon^{-Kt/R_n} \tag{18}$$

which K is substituted for the constants in the exponential.

It is evident that $(E-I_LR_n)/K_s=S_{mn}$, the maximum speed attainable on the considered resistor step, so that

$$s=S_{mn}+(S_{v(n-1)}-S_{mn})\epsilon^{-Kt/R_n} \tag{19}$$

Thus, at time equal to infinity the speed curve becomes assymptotic to the ordinate S_{nm}. However, at some intermediate time, T_n, the current becomes I_v, and the accelerating relay causes switching to the next resistor step. This is shown in figure 2*a*.

Substituting into equation 19 the value of s obtained from equation 1 yields

$$i=I_L+(I_p-I_L)\epsilon^{-Kt/R_n} \tag{20}$$

This equation is graphically shown in figure 2*b*.

Let T_n represent the time in seconds on the nth step for the current to die from the peak to the valley value, and T the total starting period. Then from equation 20,

Table I. NEMA Resistor Classification Table

Per Cent Full-Load Current on First Point of Controller	Cycle and Corresponding Class Number: 30 Sec. on Out of 15 Min.	5 Sec. on Out of 80 Sec.	10 Sec. on Out of 80 Sec.	15 Sec. on Out of 90 Sec.	15 Sec. on Out of 60 Sec.	15 Sec. on Out of 45 Sec.	15 Sec. on Out of 30 Sec.	Continuous	Approximate Starting Torque in Per Cent of Full-Load Torque: Series Motors	Shunt Motors	Wound-Rotor Motors Three Phase
25	101	111	131	141	151	161	171	91	8	25	25
*50	102	112	132	142	152	*162	*172	92	30	50	50
70	103	113	133	143	153	163	173	93	50	70	70
100	104	114	134	144	154	164	174	94	100	100	100
150	105	115	135	145	155	165	175	95	170	150	150
200 or more	106	116	136	146	156	166	176	96	250	200	200

* Class 162 and 172 a-c mine-hoist resistors shall be designed for $33^1/_3$ per cent current on first point of controller.

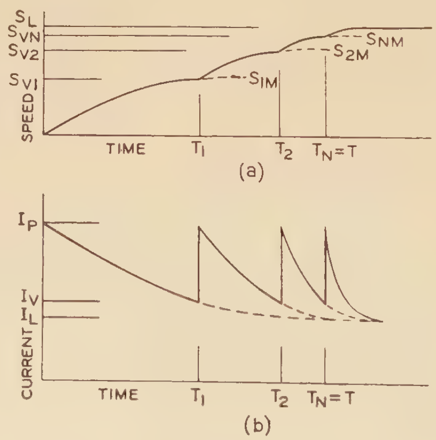

Figure 2

(*a*)—Speed-time curves for motor during acceleration

(*b*)—Current-time curves

$$T_n = (R_n/K)2.3 \log_{10} (I_p - I_L/(I_v - I_L) \quad (21)$$

Hence

$$T_{(n+1)} = T_n R_{(n+1)}/R_n = T_n/X \quad (22)$$

Inasmuch as the total starting time is equal to the sum of the time on all steps, the time on the first step is given by

$$T_1 = T/(1+1/X+1/X^2+\ldots+1/X^{N-1})$$
$$= TX^{N-1}(X-1)/(X^N-1) = C_T T \quad (23)$$

C_T is a constant defined by the equation. See table II.

Knowing the total starting time, equations 22 and 23 can be used to calculate the accelerating time on each step. *For time-limit acceleration the relays should be set so that the time ratio for the successive steps is equal to* X.

The total period the nth resistor step is in the circuit is $T_1+T_2+\ldots+T_n$. Let this be represented by P_n. Then,

$$P_n = T_1(1+1/X+1/X^2+\ldots+1/X^{(n-1)})$$
$$= T_1(X^n-1)/(X-1)X^{(n-1)} \quad (24)$$

The time of duty as given by the classification number does not necessarily give the starting period of the motor. Thus, in a 130 class instead of 10 seconds it may require but 5 seconds to start, with two starts in the 80-second period. However, the most severe condition for a given class is for a single start to occupy the whole of the allowed service time. Therefore,

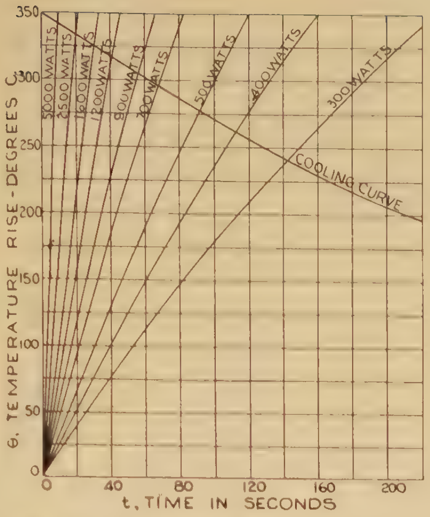

Figure 3a. Time-temperature curves for a starting resistor

a resistor designed on this basis will be in every case adequate.

RMS Current

Often the current I_L required by the load during starting and the constant K in equation 20 may not readily be ascertained by the engineer who must lay out the resistor. For a given motor, resistor class, and number of steps, K and I_L are not mutually independent, however, and if I_L is fixed K is determined. The time for the current to decay from peak to

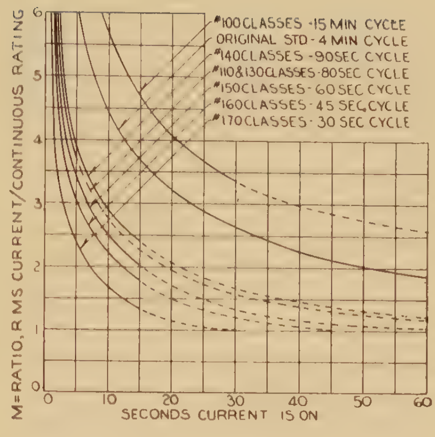

Figure 3b. Cyclic-capacity curves for a starting resistor, showing the ratio, M, of the short-time rms current to the continuous-current rating of the resistor elements, plotted against the time the current is on for the various duty cycles specified by the resistor class numbers

valley value is fixed by the class number. Figure 5 shows a family of curves calculated for various assumed values of I_L. It is evident that the condition for highest rms starting current is for I_L to be equal to zero, and that this value does not differ radically from the rms value for most practical cases. On the assumption that I_L is zero, the rms current from equation 20 is, for the nth step,

$$I_{\text{rms}} = I_p\sqrt{R_n(1-\epsilon^{-2KT_n/R_n})/2KT_n} \quad (25)$$

As shown by equation 21, the ratio R_n/T_n is constant for all values of n, so that we may draw the very convenient conclusion that the rms current is the same for all steps. The value of T_n/R_n may be obtained by substituting 0 for I_L in equation 21. It follows that

$$I_{\text{rms}} = C_I I \quad (26)$$

where

$$C_I = I_{\text{rms}}/I = Y\sqrt{(1-1/X^2)/4.6 \log_{10} X} \quad (27)$$

Values of C_I for the various classes are given in table II.

Cyclic Capacity of Resistor Units

In order to apply table II to practical resistor design, it is necessary to know the cyclic capacity of the resistor elements. Such curves can be calculated from the dimensions and the physical and heat dissipation constants of the resistor. They may take the form of families of curves, showing the characteristics of each particular size of resistor element for various duty cycles, or inasmuch as these will be similar, may be

Table II. Constants for Calculation of NEMA Accelerating Resistors for Shunt-Wound D-C Motors and A-C Three-Phase Wound-Rotor Induction Motors, Wye Resistor Connection

First two figures of class number	10	11	13	14	15	16	17
T (seconds)	30	5	10	15	15	15	15

Last Figure of Class Number:		1	2	3	4	5	6
Number of Steps (N)	Y	0.25	0.50	0.70	1.00	1.50	2.00
	$U_{\text{D-C}}$	3.9	1.9	1.33	0.90	0.57	0.40
	$U_{\text{A-C}}$	2.2	1.0	0.77	0.52	0.32	0.23
1	X	40.0	20.0	14.27	10.0	6.67	5.00
	C_r	1.00	1.00	1.00	1.00	1.00	1.00
	C_I	0.092	0.204	0.291	0.464	0 762	1.092
	C_T	1.00	1.00	1.00	1.00	1.00	1.00
2	X	6.325	4.472	3.3780	3.162	2.2582	2.236
	C_r	0.1365	0.1824	0.2085	0.2402	0.2776	0.309
	C_I	0.131	0.282	0.413	0.625	1.002	1.402
	C_T	0.862	0.817	0.792	0.760	0.720	0.687
3	X	3.420	2.714	2.427	2.154	1.882	1.710
	C_r	0.0622	0.0902	0.1072	0.1282	0.1547	0.1775
	C_I	0.1505	0.329	0.477	0.711	1.128	1.564
	C_T	0.723	0.659	0.625	0.592	0.550	0.515
4	X	2.515	2.115	1.944	1.778	1.607	1.495
	C_r	0.0388	0.0587	0.0708	0.0865	0.1065	0.1237
	C_I	0.1685	0.358	0.519	0.770	1.205	1.656
	C_T	0.631	0.555	0.524	0.478	0.447	0.415
5	X	2.091	1.821	1.702	1.585	1.461	1.380
	C_r	0.0280	0.0432	0.0527	0.0650	0.0809	0.0950
	C_I	0.1795	0.381	0.548	0.807	1.254	1.714
	C_T	0.533	0.475	0.445	0.412	0.373	0.350
6	X	1.849	1.648	1.558	1.468	1.373	1.308
	C_r	0.0218	0.0341	0.0419	0.0520	0.0654	0.0770
	C_I	0.1892	0.400	0.568	0.835	1.291	1.756
	C_T	0.472	0.415	0.385	0.352	0.320	0.297
7	X	1.695	1.533	1.462	1.389	1.311	1.259
	C_r	0.01779	0.0281	0.0347	0.0432	0.0546	0.0647
	C_I	0.1962	0.409	0.584	0.857	1.318	1.690
	C_T	0.426	0.368	0.342	0.311	0.286	0.257

shown as one curve for each duty cycle in terms of the ratio M of the rms current to the normal element rating, I_c, plotted against the time P_n the particular step carries current during each cycle of operation, as shown in figure 3b.

Sample Calculation

Assume a class 135 resistor for a 50-horsepower 230-volt d-c shunt motor, and that the valley current shall be not less than 100 per cent of the full-load current, 190 amperes.

Then $X=I_p/I_v=1.5$ approximately.

Referring to table II, under the 5 class, it is seen that a five-step resistor (six-point controller) is required, the nearest value of X being 1.461. The corresponding value of U is 0.57.

The total resistance is $R=UE/I=$ 0.69 ohm, and r_N is $C_rR=0.0809R=$ 0.0557 ohms. The resistances for the fourth, third, second, and first steps are determined by multiplying successively by X.

The duty cycle for the 130 class is 10 seconds on out of 80 seconds. Hence T is 10 seconds, and T_1 is $C_TT=0.373\times 10=3.73$ seconds. The rms current is $C_II=1.254$ times full load, or 239 amperes. This divided by M, the I_{rms} to element rating ratio (4.17) read from the curve figure 3b for the 130 class at

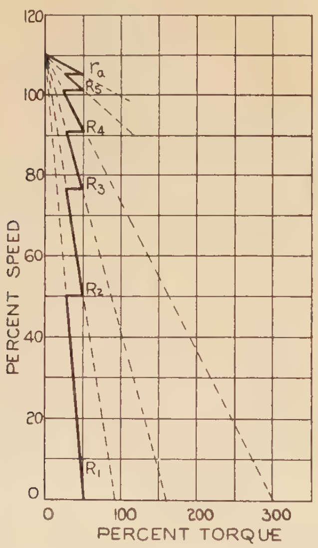

Figure 4a. Speed-torque curves for a five-step 2-class resistor, based on acceleration

3.73 seconds gives the element rating for the first step. The time on each point of the controller is determined by dividing the time on the previous point by X, and the "on" period is obtained by cumulative addition of those values, as shown in table III.

From a table of standard resistors (having the characteristics given by the curve) elements are chosen having continuous ratings equal to or greater than those calculated, and a sufficient number of each are connected in series to give the proper resistance for the respective steps.

Regulating Resistors

Many of the NEMA resistor classes are inherently regulating. This is obviously true of the 90 classes, which are for continuous duty. The 150, 160, and 170 classes being designed for $^1/_4$, $^1/_3$, and $^1/_2$ duty cycles are evidently adapted to intermittent regulating duty. When on the first point of the controller they give currents greater than 100 per cent full load, the resistance and capacity for the successive steps may be laid out in accordance with the theory as previously outlined for accelerating resistors. However, with less than full-load current on the first step, they must be designed on a different basis. Consider for example a class 172 resistor having five steps.

In figure 4a are shown the speed torque curves laid out on the basis of acceleration with equal 50 per cent current peaks on all steps. It is evident that there can be little practical application for such a resistor, for the motor could operate only without load. However, for hoist duty, a high resistance on the first step is desired while taking the slack out of the hoisting cable. On subsequent steps, the resistor is required to give speed regulation while carrying full-torque load. With the resistor of figure 4a the load will not be started until the third point is reached, when 156 per cent torque will be developed, and a maximum speed of 42 per cent will be attained.

In figure 4b, is shown the speed-torque relation for a class 172 resistor based on speed regulation. Here approximately 120 per cent torque is available on the second point, giving a slow pickup, and a maximum speed of 20 per cent. The succeeding points give 50, 80, and 93 per cent speeds, respectively. The capacities of the various steps must necessarily be arbitrarily set at values which experience has indicated are adequate for usual conditions of service in regulating duty of this type.

A-C Three-Phase Wound-Rotor Induction Motor

In the case of an a-c wound-rotor three-phase motor, with the resistor wye-connected in the secondary, the speed, torque, and secondary-current relations are similar to those of the d-c shunt-wound motor. If in this case we let E and I represent the normal secondary voltage and current, respectively, the total resistance per phase is

$$R=E(1/\sqrt{3}Y-Z)/I=UE/I \tag{28}$$

Assuming values of Z between 0.05 and 0.1, U takes the values given in table II.

Except for this different value of U, the calculation of the resistor is the same as for the case of the shunt-wound d-c motor.

If the resistor is delta connected the calculated resistance values should be multiplied by three and current values divided by $\sqrt{3}$.

Classes 162 and 172 a-c mine-hoist resistors, are modified by specific provision that the initial peak current shall

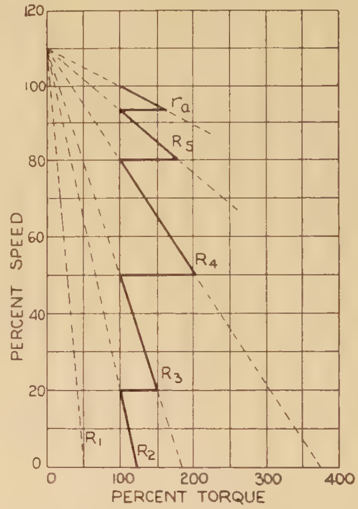

Figure 4b. Speed-torque curves for a five-step 2-class resistor, based on speed regulation

be $33^1/_3$ per cent of full load. The class 162 for vertical hoists is designed for 340 watts per horsepower, and the class 172 for slope hoists for 510 watts.

Acceleration With Unequal Current Peaks

If, instead of switching when the valley currents are I_v, the accelerating relays are set to operate at some other value I_v', then on all points after the first, the current peaks will be I_p', as shown in figure 1 From similar triangles,

$$I_p'/I_v'=I_p/I_v=X \tag{29}$$

Let the ratio I_v/I_v' be represented by G. By symmetry, from equation 21, assuming $I_L = 0$ as before, we have,

$$T_1'=T_1(\log I_p/I_v')/\log I_p/I_v=AT_1 \tag{30}$$

where

$$A = \log GX/\log X \tag{31}$$

Also, for $n > 1$,

$$T_n' = T_n(\log I_p'/I_v')/\log I_p/I_v = T_n \tag{32}$$

Hence, the time on all points of the controller may be calculated as in the previous cases, then the time on the first point modified by multiplying by A, and the period each resistor step is in the circuit obtained by cumulative addition.

On the first point, from equation 25, since from equation 21, $KT_1'/R_1 = \log GX$, the rms current is $C_{I1}'I$, where

$$C_{I1}' = Y\sqrt{(1 - 1/G^2X^2)/4.6 \log_{10} GX} \tag{33}$$

For the other points, from equation 25, S. Solving for s at the instant of switching, when $r = R_n$ and $i = I_v$, and substituting this value into the equation with $r = R_{(n+1)}$ and $i = I_p$, we find that all steps have equal resistances,

$$r_n = R_n - R_{(n+1)} = R_1(X-1) = R/N \tag{35}$$

The desired valley current determines the number of steps, N. This is most conveniently used as a ratio, V, to full-load current.

$$V = I_v/I = Y/[1 + 1/(N+1)] \tag{36}$$

In practice it is customary to taper the resistance values of the steps a few per cent, the first being the highest, in order to minimize the effects of inequality between the resistance of the steps and that of the armature plus field and leads.

Table III

Resistance Per Step	Accelerating Time	Period on Each Step	$M = I_{rms}/I_c$	I_c = Element Rating
$r_1 = 0.1750X = 0.2560$	$T_1 = 0.373T = 3.73$	$P_1 = T_1 = 3.73$	4.17	.57
$r_2 = 0.1196X = 0.1750$	$T_2 = 3.73/X = 2.545$	$P_2 = P_1 + T_2 = 6.275$	3.35	.71
$r_3 = 0.0817X = 0.1196$	$T_3 = 2.545/X = 1.735$	$P_3 = P_2 + T_3 = 8.010$	3.01	.79
$r_4 = 0.0557X = 0.0817$	$T_4 = 1.735/X = 1.185$	$P_4 = P_3 + T_4 = 9.195$	2.87	.83
$r_N = 0.0809R = 0.0557$	$T_5 = 1.185/X = 0.805$	$P_5 = P_4 + T_5 = 10.000$	2.75	.87
0.6880	10.000			

Table IV. Constants for Series-Connected D-C Motors

Last Figure of Class Number	Y	U	Constant	Number of Steps 2	3	4	5	6	7
5	1.50	0.57	V	1.125	1.200	1.250	1.286	1.312	1.333
			C_r	0.500	0.333	0.250	0.200	0.167	0.143
			C_I	1.240	1.312	1.350	1.370	1.395	1.400
			C_T	0.500	0.333	0.250	0.200	0.167	3.143
6	2.0	0.40	V	1.500	1.600	1.667	1.718	1.750	1.780
			C_r	0.500	0.3333	0.250	0.200	0.167	0.143
			C_I	1.70	1.77	1.81	1.84	1.86	1.88
			C_T	0.500	0.333	0.250	0.250	0.167	0.143

since $T_n = T_n'$, and $I_p' = YI/G$, the rms current is equal to $1/G$ times the rms current for equal current peaks, or $C_I I/G$.

The rms current for the complete period on any step is the weighted average for the time it is in the circuit.

Series-Wound D-C Motors

For series wound motors, the electromotive-force equation becomes

$$E = ir + K_s si \tag{34}$$

in which the constant K_s is determined at rated current, I, and rated speed, This is particularly necessary with small values of Y and N.

In the series motor, torque (neglecting saturation) is proportional to the square of the current, so that the torque equation becomes $i^2K_t = 0.105Jds/dt + L$, in which $K_t = L/I_L^2$, and the load is assumed constant. The solution is

$$t = 0.105JIEB/K_sL$$

$$B = 1/I_p - 1/i + \frac{1.15}{I_L}\log_{10}\frac{(I_p - I_L)}{(i_p + I_L)}\frac{(i + I_L)}{(i - I_L)} \tag{37}$$

These being free from terms in r, indicate that the time and the rms currents are equal, respectively, on the several accelerating steps. The period any step is in the circuit is, therefore,

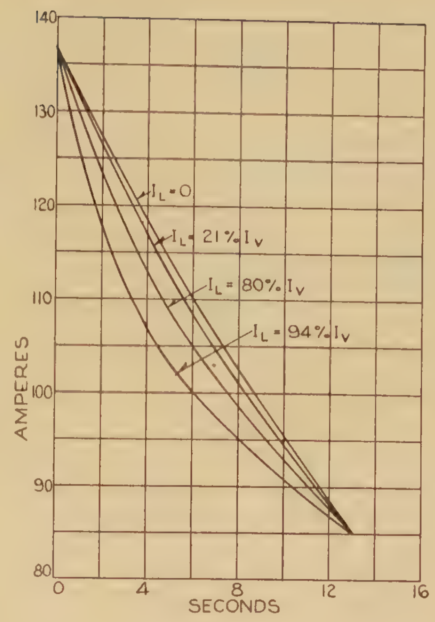

Figure 5. Curves showing the effect upon the current-time curve of varying the load component of the armature current, for fixed values of I_p, I_v, and T_1

$$P_n = nT_n = nT/N = nC_TT \tag{38}$$

The rms current on each step is (for $I_L < I_v$)

$$I_{rms} = I_L\sqrt{1 + (1/I_v - 1/I_p)/B} \tag{39}$$

Here in the expression for B, $i = I_v$. (I_v must be greater than I_L.) For the 5 and 6 classes I_L is generally equal to the full-load current, I, and the constants for these classes are shown in table IV.

List of Symbols and Equations

Y = fraction of full-load current on first point
E = normal voltage
I = normal current
R = total ohmic value of resistor
X = ratio of peak to valley current
U, C_r, C_I, C_T, M, and V are constants evaluated in tables and curve
T = total time R is in circuit as defined by class number
N = number of resistor steps
$T_1 = P_1$ = time first resistor step is in circuit
P_n = time nth step is in circuit
r_N = resistance of last step
r_n = resistance of nth step
I_c = element rating
$R = UE/I$
$r_N = C_rR$
$r_{(n-1)} = Xr_n$
$T_1 = P_1 = C_TT$
$T_{(n+1)} = T_n/X$
$P_{(n+1)} = P_n + T_{(n+1)}$
$I_{rms} = C_II$
M = constant from figure 3b for P_n
$I_c = I_{rms}/M$

Protector Tubes for Power Systems

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AFTER eight years' experience with the design, application, and operation of the protector tube, it is considered an opportune time to review this experience and propose the standardization of this device.

Protector tubes have been applied to practically every type of system, with a total of approximately 50,000 now in operation and for a range in voltage of 13.8 to 230 kv inclusive. In the light of this broad experience it is the purpose of this paper to summarize the present conception of the theory of the operation, the factors that should be considered in the characteristics of the device, the characteristics of the system, and then suggest a standardization of the device to simplify its application. This joint paper was undertaken at the request of the lightning-arrester subcommittee of the AIEE protective-devices committee.

Theory of Tube Operation

Since the protector tubes are to prevent flashover of line insulation the prime requirements are that their discharge voltage be lower than the flashover voltage of the insulation which they are protecting and they must also be capable of interrupting the generated follow current. Operation may be more readily understood by first considering the phenomena involved in current interruption. After the surge currents are discharged to ground, the normal-frequency or generated current may follow and in order to have satisfactory operation, the protector tube must have a rate of insulation recovery after generated-current zero greater than the rate at which the system voltage recovers. This can best be explained by considering the recovery voltage on a simple circuit.

Such a circuit shown in figure 1 possesses the basic elements required to illustrate the transient recovery voltage, following interruption of fault current. This circuit contains lumped constants of L, R, and C in such proportion that it will have a natural frequency of oscillation. When a fault is placed at F and later removed at a normal-current zero, an oscillating voltage will appear across the capacitor, which will be composed of the normal-frequency voltage and a voltage whose frequency corresponds to the circuit's natural frequency. The simplest method of developing the oscillating voltage is to consider the generated voltage and oscillating voltage separately. At the instant the fault is removed, the voltage across the fault must be zero. This condition of zero voltage is satisfied if it is assumed that there is a natural-frequency voltage that appears instantly equal and opposite in magnitude to that of the generated voltage. The sum of these two voltages V_R is therefore the recovery voltage of the circuit. The time to crest of the oscillation is approximately proportional to $\sqrt{LC}$. Therefore if either L or C is increased, the time to the recovery-voltage crest of the natural-frequency oscillation will increase. This conception is important as the L of the source and C of the line vary for different line conditions. Theoretically, the natural-frequency voltage will start equal to the generated voltage at the instant the fault is removed assuming no losses, and oscillate about this voltage as an axis. However, losses produce damping and this natural-frequency component will decay at a rate depending upon the losses in the circuit.

When a protector tube is discharged by lightning and power follow current flows through the tube, it must have the properties of changing from a good conductor to a good insulator for satisfactory operation. In any interrupting device it takes time to establish the insulating characteristics which are commonly called the insulation recovery characteristics of the device. The interruption is therefore a race between the insulation recovery strength of the device and the voltage recovery on the system. Curve A of figure 2 is the recovery voltage for a more complicated system. Instead of having simple oscillations as in figure 1 the recovery voltage is now a more complicated function of time as the result of a succession of traveling waves on the line.

Curves B, C, and D of figure 2 are hypothetical insulation-recovery curves for a protective device. If the protective device has the characteristics shown in curve B and the system recovery characteristics are as shown in curve A, then the interruption will be satisfactory, as the insulation recovery of the device is faster than the voltage recovery on the system. On the other hand, if the protective-device insulation recovery strength is as shown in curve C or curve D, then the system recovery voltage overtakes the insulation recovery strength at second or first crest, respectively, restriking will take place, and if this occurs at more than two consecutive current zeros, the operation is in general not considered satisfactory. It is therefore possible to predetermine the operation of tubes on a system by comparing the insulation recovery strength of the tube and the system recovery voltage.

The protector-tube insulation-recovery curves and the voltage-recovery curves will vary for each current value. For a

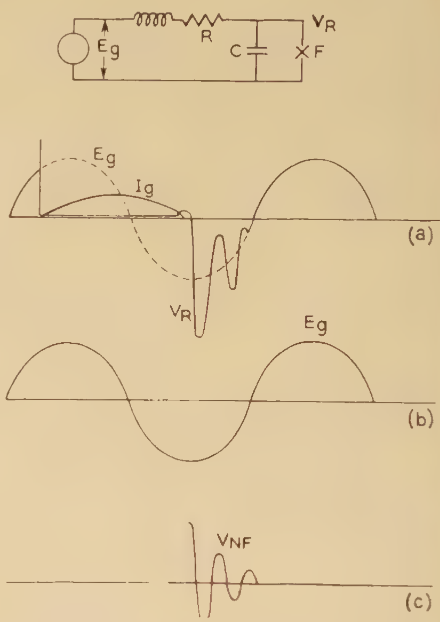

Figure 1. Elements of recovery voltage

E_g —Generated voltage
I_g —Generated current
V_R —Protector-tube voltage
V_{NF}—Natural-frequency voltage

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given short-circuit current the protector-tube insulation-recovery curves also are lower with increased bore. Thus if the protector tube, when new, starts with a characteristic such as shown in curve *B*, figure 3, as it erodes the bore will increase and the curve will drop until at curve *C* it will fail to give satisfactory interrupting characteristics. It is for this reason that the rate of erosion must be considered in protector-tube design. Likewise, the same tube will have different insulation-recovery curves for different values of current. Curve *A*, figure 4, may be the insulation recovery strength for maximum current, and the insulation recovery strength for minimum current might be of the order of curve *B*, of this figure. Thus the system recovery-voltage curves must be compared with the insulation recovery strengths of the protective device to see that operation will be correct. The following discussion will therefore deal with system characteristics and protector-tube characteristics showing how this has been done to arrive at a standard line of protector tubes.

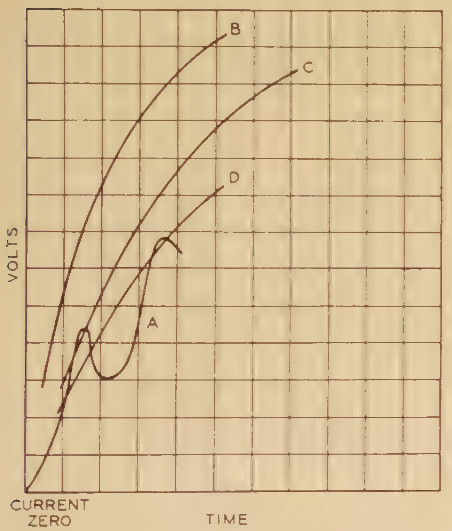

Figure 2. Elements of protector-tube operation

A—Recovery voltage of complex system
B, C, D—Protector-tube insulation recovery curves

System Characteristics

General Consideration

Since protector tubes are connected between line and ground, it is necessary that the system characteristics which affect tube performance be determined as viewed from the tube location. It is therefore obvious that to make a successful application the single, double, and triple line-to-ground follow currents and corresponding recovery voltages must be evaluated.

A number of factors will determine the magnitude of the currents and the associated recovery voltages. For example:

1. Method of grounding the system neutral, that is, solid grounding, resistance or reactance grounding, or any combination of these.
2. Minimum and maximum connected system capacity (variation in operating conditions).
3. Length of connected circuit or lines in miles and relative location of short-circuit-current sources.
4. Line configuration and presence of overhead ground wires.
5. Tower-footing resistance.
6. Protector-tube location.

(a) *Determination of the Short-Circuit Current Range*

The three-phase short-circuit current is in general the maximum current obtained, except near the system grounding points where the line-to-ground current may be greater. The single-line-to-ground current should be determined both with and without the effects of tower-footing resistance.

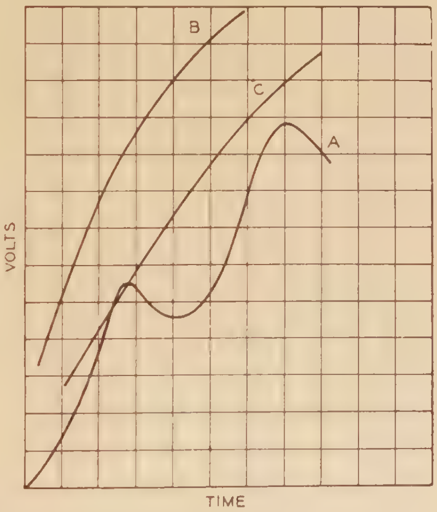

Figure 3. Effect of erosion on protector-tube operation

A—Recovery voltage of complex system
B, C—Protector-tube insulation recovery

The double-line-to-ground currents will usually be between the values obtained for single-line-to-ground and triple-line-to-ground faults. However, there may be exceptions for low ratios of zero to positive-sequence reactance and for high values of circuit resistance. Usually, such deviations are quantitatively unimportant.

Where the line is long or the system is extensive and the short-circuit currents vary widely, the application of tubes can be helped by plotting a current profile of the line (or lines) and zoning the tubes. Figure 5 shows such a profile for an assumed system. It may be noted that the maximum currents are at the generating and system ground points, which is usually the case for a solidly grounded-neutral system. By zoning the tubes it is possible to use tubes having a lower maximum rating in many locations, thereby obtaining tubes capable of operating successfully on lower currents or with higher tower-footing resistances.

When possible, it is desirable to take into account future system growth and its effect upon the currents to which the tube may be subjected.

While it is necessary to determine both the maximum and minimum currents that the tube may be called upon to interrupt, it is equally and perhaps more important to evaluate the currents expected under normal conditions. In doing this it may become quite evident that a particular system condition is imposing altogether too severe restriction on the tubes relative to the probability of that condition being obtained. The system condition which comes under this classification may occur when part of the system is temporarily disconnected.

When determining short-circuit currents it is only necessary to determine the rms symmetrical short-circuit current, as the design of the tube is such as to allow for the maximum asymmetrical current which may normally be expected in a power circuit. Since protector tubes

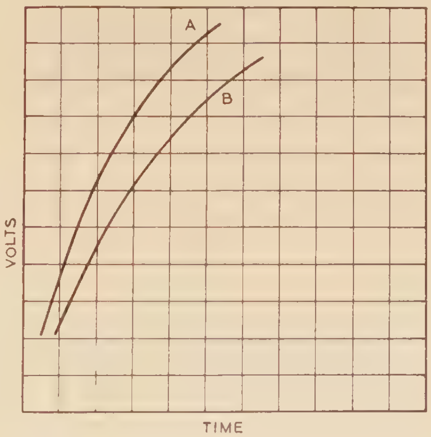

Figure 4. Effect of current on protector-tube operation

A—Tube insulation recovery, maximum current
B—Tube insulation recovery, minimum current

usually interrupt within the first cycle, subtransient values of synchronous-machine reactances should be used in current calculations. For fault locations which are remote electrically from large rotating equipment, generators, or synchronous condensers, it may be necessary to consider the effect of rotating motor loads as both synchronous motors and induction motors will contribute short-circuit currents. In general, this is an important factor only when the tubes are located electrically at some distance from the source of system supply or generation. The method of symmetrical components may be used for the calculation of the short-circuit currents. A-c network calculators or network analyzers may be used to advantage when available. These methods are well known and are fully described in the literature.

(*b*) *System Recovery Voltage Characteristics*

It has been shown above that the tube's dielectric-strength recovery must exceed the system voltage recovery in order to prevent a restrike in the tube and possibly failure to interrupt.

It is evident that in general the complete voltage-recovery characteristic is necessary in order to determine tube performance. The effect of system characteristics on the voltage-recovery characteristics has been given a great deal of study,[1–4] particularly by the use of miniature or equivalent systems. By this method, the effect of the various system

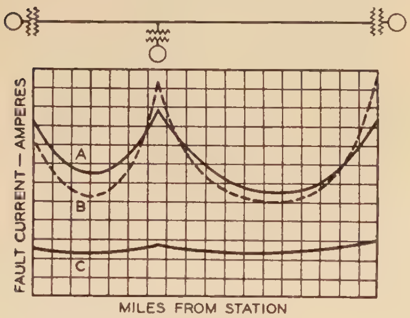

Figure 5. Typical fault-current profile

A—Three-phase fault current
B—Line-ground fault current (zero resistance)
C—Line-ground fault current (100-ohm ground resistance)

factors can be simulated and evaluated. Field tests have been made which have checked the equivalent system method of analysis. From the results of these studies, the influence of the various system factors can be evaluated and tube applications made accordingly.

1. For all numbered references, see list at end of paper.

(1) *Solidly Grounded Systems.* The solidly grounded system which has all sources of short-circuit current solidly grounded, is a representative type of system found particularly at the higher voltages. The effect of tower-footing resistance is to reduce the current and to reduce the magnitude of recovery voltages across the tube. This resistance reduces the recovery voltage on account of the improvement of the power factor in the circuit which means that at current zero or time of interruption, the instantaneous fundamental-frequency voltage is of lower magnitude than for a pure reactive circuit. However, there is a lower limit to which the current can be reduced and still have successful operation. The limits will be discussed later in this paper.

(2) *Systems Grounded Through Resistance.* For practical purposes the effect of system neutral resistance is similar to the effect of tower-footing resistance discussed above. In cases where both neutral-grounding resistance and tower-footing resistance are encountered, they should be considered as being in series. Thus the same limits apply as pointed out for solidly grounded systems with tower-footing resistance alone. If the sum of those resistances is such that a single protector tube does not have the current range to interrupt both the phase currents not limited by resistance and the single line-to-ground currents limited by resistance, then the use of four protector tubes can be considered where three protector tubes of a high current rating are connected in star and the star point connected to ground through a protector tube of lower current rating.

(3) *Systems Grounded Through Reactance.* When the system neutral (or neutrals) is grounded through reactance, standard protector tubes for solidly grounded service may be applied under conditions such that the zero-sequence reactance viewed from the protector tube locations is not more than three times as great as the positive-sequence reactance. When the ratio of X_0 to X_1 is greater than this special consideration must be given to the protector tube. However, in a large number of cases the protector tube for the next higher voltage rating will be applicable. When the protector tubes are used on a system using a tuned value of reactance or using a ground-fault neutralizer, the line-to-ground currents should not have to be cleared by the tube. Thus protector tubes built for line-to-line voltage can be applied on the basis of the line-to-line fault currents only.

(4) *Isolated-Neutral System.* Protector tubes applied on an isolated-neutral system must be given special consideration, as the single-line-to-ground current (charging current) will usually be below the minimum current rating for the suggested standard tube. In connection with the application of protector tubes to isolated-neutral systems consideration should be given to the four-tube scheme as such a scheme should ease the problem of interrupting charging current.

(5) *Lightning Severity.* Investigations indicate the possibilities of lightning strokes of the order of 200,000 amperes although the probability of getting a stroke in excess of 100,000 amperes is very remote as indicated by actual field data. Furthermore, several tubes may share the lightning discharge current with the result that the duty on each tube is reduced. Operating experience with protector tubes over an eight-year period indicates that the existing designs are adequate for the vast majority of surge currents encountered.

(6) *Relay Settings.* It has been found in service that systems using protector

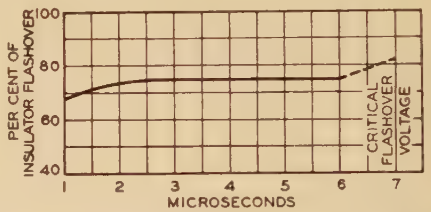

Figure 6. Relative volt-time characteristics of protector tubes and insulators

1½x40-microsecond positive wave
115-kv protector tube versus seven standard disk insulators

tubes should not have relay settings less than two cycles. Where relays have a shorter operating time, it will be necessary to introduce a delay to prevent unnecessary circuit outages.

Protector-Tube Characteristics

(a) Impulse Protection Level

Since the protector tubes are used to prevent the flashover of line insulators, their primary characteristic must be a discharge-voltage value lower than that of parallel insulators which they protect. This requirement naturally serves to limit the length of the protector tube between electrodes. The devices are installed with an air gap in series, provided for the purpose of withstanding the normal impressed voltage to avoid possible corona or leakage currents across the protector tube itself. In general, the spac-

ing of this air gap is considerably less than the spacing between the protector tube electrodes. Consequently, this series air gap will not add greatly to the over-all discharge voltage value of the applied protector tube. The impulse-discharge voltage level of protector tubes is best shown in the form of a volt-time curve. Such curves have been generalized for protector tubes, a typical curve being shown in figure 6 for the positive $1\frac{1}{2}$x40-microsecond wave. It should be noted

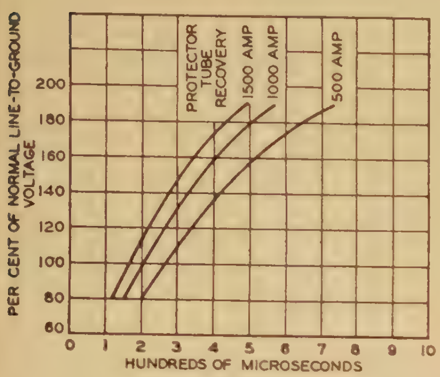

Figure 7. Effect of current on recovery voltage of protector tube

that the volt-time characteristic of the protector tube is flatter than that of insulators.

As illustrated in figure 6 it can be shown that where the protector tube gives protection to an insulator on the positive $1\frac{1}{2}$x40-microsecond wave at the critical flashover point, the protector tube will in general also protect for waves rising to flashover in shorter times or on negative polarity. Therefore, a comparison of the margin existing between the protector tube and the insulator based on the $1\frac{1}{2}$x40 positive wave may be taken as a yardstick for determining whether or not a sufficient margin exists between the level of the protector tube and the insulator. To aid in the application of protector tubes, table I has been prepared to show the discharge level of protector tubes. The table includes the minimum tight-string metal-to-metal arcing distance which the tube is expected to protect. These values include a factor of ten per cent between the actual discharge voltage of the protector tube and the impulse flashover voltage corresponding to the dry arcing distance. It is felt that 10 per cent represents the minimum margin which should be used in any case. Sufficient clearance should be provided between the protector tube and the structure to which it is attached to assure that lightning flashover will be confined within the protector tube.

(b) Tube Interrupting Characteristics as Affected by Voltage, Current, Time

It has been shown in previous papers presented to the Institute that for a given design the ability of a protector tube to function properly is a function of voltage and time for a fixed current. Likewise, this characteristic varies with the magnitude of current through the tube. These properties are illustrated in figure 7.

(c) Effect of Bore and Tube Erosion

When the protector tube operates, a part of the fiber wall is volatilized, creating a stream of rapidly moving gases which quench the arc. This volatilization of the fiber results in an increase in the tube-bore diameter. As the bore of the tube increases in diameter, the clearing characteristics of the tube undergo a change, the effect being to increase the required clearing current for any fixed recovery voltage. Figure 8 shows how the minimum clearing current of a particular protector tube increases with bore. It may be noted in this curve that an increase in the bore diameter of approximately 30 per cent doubles the

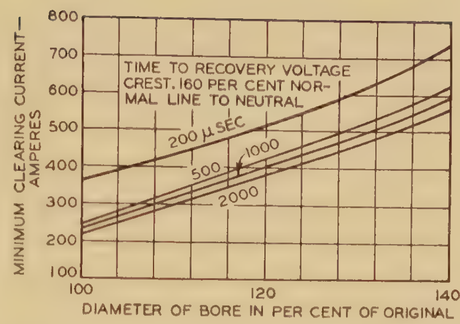

Figure 8. Effect of erosion on minimum current required for interruption

minimum current that can be cleared.

Where protector tubes are installed at every structure along the line, the probability of any protector tube having to operate a large number of times is greatly reduced, as compared to a protector tube applied at a reflection point. Over a five-year period on such a line, out of a total of 810 protector tubes, 228 tubes will operate once, 63 twice, 13 three times, 8 four times, 0 five times.[5] Also, the records of erosion of protector tubes over a six-year period on a particular line[6] indicated that no protector tubes had reached the limit of useful life. An inspection of these results leads immediately to the conclusion that where protector tubes are installed on every structure, the erosion of the bore from the standpoint of operations will not constitute a limiting factor as far as protector-tube life is concerned.

In other types of installation, such as river-crossing towers or terminal structures of lines which are not completely equipped throughout with new protector tubes, the tubes which are installed at these points will be called upon to operate more frequently. In such cases, a record should be kept both of the number of tube operations and the erosion occurring in the protector-tube bore, as it will be possible from these records to determine the time when the maximum permissible erosion of the bore is reached and when therefore the protector tube should be replaced.

(d) Impulse-Discharge-Current Capabilities

In general, protector tubes can withstand lightning-stroke currents of 50,000 to 100,000 amperes on the basis of a current wave that rises to crest in 10 microseconds and decays to half value in 20 microseconds. Experience to date with thousands of protector tubes has shown that the probability of a protector tube being burst from lightning current in excess of its discharge capabilities is small. It therefore appears that the

Table I

Circuit Voltage Rating	Tube-Discharge Critical Voltage, Representative Value Dry,* $1\frac{1}{2}$x40 Wave		Protector-Tube Impulse Discharge-Voltage Characteristics		
	Positive	Negative	Series Gap† (Inches)	Minimum Dry Arcing Distance Tube Will Protect (Inches)	Number Standard Insulator Disks Tube Will Protect; $5\frac{3}{4}$ by 10-Inch Spacing
13.8	100	110	3/4	6	1
23	150	155	1 1/2	9	2
34.5	200	220	2	12 1/2	2
46	260	285	3 1/4	17	3
69	375	420	5 1/2	28	5
92	475	540	8 1/2		6
115	575	635	11		7

* Actual values will vary somewhat, depending on the design and mounting of the tube.

† These are recommended minimum series gaps. Under no conditions of operation should the series gap be less than 80 per cent of the recommended minimum.

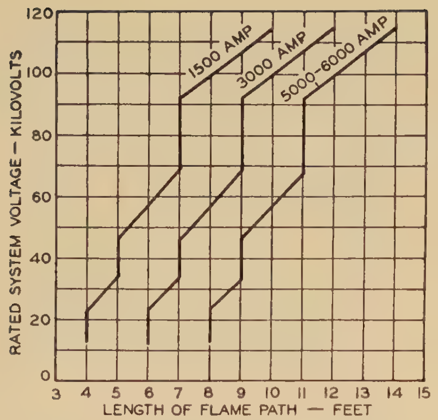

Figure 9. Visible flame path as a function of power, current, and voltage

impulse-discharge capabilities of protector tubes are sufficient to withstand all but the most severe direct strokes.

(e) Effect of Weather

Insufficient time has elapsed since the protector tubes have been in service to form a definite opinion as to the ultimate life expectancy from the standpoint of weathering. The outside finish on tubes has been improved. The experience, with modern finishes, indicates good weathering characteristics. The exact performance will depend on the local atmospheric conditions. Periodic refinishing of protector tubes with a good paint will increase their weather resistance.

(f) Discharge Gases and Recoil Forces

The ionized gases must be properly directed to avoid flashovers due to their conductivity. Figure 9 shows the length of the visible flame path as a function of the power current and voltage. Obviously, the circuit voltage and the protector-tube dimensions should be considered when establishing the safe strike distance from the gas envelope to the object of different potential.

Recoil forces must be considered when designing the mounting hardware. It is of importance that the mounting hardware be designed to facilitate ease of installation. This results in a direct saving to the operator, and broadens the field of application of the device.

Proposed Standard Protector Tubes

In order to facilitate the application of any device, it is desirable to have standards. This very aptly applies to the protector tube because of the large number of variables that enter into its application. It is for this reason that considerable thought has been given to the requirements for such a standardization. Based on the large amount of work done on miniature systems and eight years experience with the operation of protector tubes in the field, requirements for a proposed line of protector tubes are presented in table II.

When establishing the requirements for a standard line of protector tubes, it is necessary to select system conditions having recovery-voltage characteristics of sufficient severity to cover the vast majority of applications and from this determine the tube design. The maximum rating of the protector tube may be determined by either the insulation-recovery characteristics or the bursting strength of the tubes. The minimum current rating is determined by the amount of allowable erosion after operation at maximum current rating.

Since the capacitance of the system (a function of the length of line) and the reactance of the system are the major factors in determining recovery-voltage conditions of the system, it is essential to fix some minimum length of line which establishes the maximum permis-

Table II. Recovery-Voltage Characteristics for Which Proposed Standard Tubes Are Designed

System Kilovolts	Minimum Miles of Line*†	Tube Current Rating** Minimum	Tube Current Rating** Maximum	Minimum Current, Maximum Significant Crest: Per Cent Voltage	Minimum Current, Maximum Significant Crest: Time (Microseconds)	Maximum Current, First Crest: Per Cent Voltage	Maximum Current, First Crest: Time	Maximum Current, Maximum Significant Crest: Per Cent Voltage	Maximum Current, Maximum Significant Crest: Time
13.8	10	300	1,500	160	230	90	55	165	130
		400	3,000	160	230	90	35	160	120
		600	6,000	160	200	90	25	160	120
23	15	300	1,500	165	400	73	65	165	250
		400	3,000	165	400	86	45	160	190
		600	6,000	165	400	94	30	158	190
34.5	22.5	300	1,500	170	600	65	80	165	390
		400	3,000	170	600	85	60	159	270
		600	6,000	170	600	100	50	156	270
46	30	300	1,500	165	800	70	115	165	530
		400	3,000	165	800	90	80	159	370
		900	6,000	165	750	105	70	153	330
69	45	400	1,500	165	1,100	85	180	165	800
		600	3,000	165	1,100	105	140	158	590
		900	5,000	165	900	115	100	149	490
92	60	400	1,500	160	1,300	88	240	165	1,070
		600	3,000	160	1,300	104	220	157	930
		1,000	5,000	160	1,100	115	180	145	760
115	75	500	1,500	160	1,450	90	300	165	1,350
		600	3,000	160	1,450	98	300	156	1,270
		1,000	5,000	160	1,350	105	300	140	1,100
138	90	500	1,500	160	1,600	90	350	165	1,440
		600	3,000	160	1,600	90	350	155	1,320
		1,000	5,000	160	1,500	90	390	136	1,250

* Miles listed are the minimum circuit miles of overhead line connected or equivalent where the line has a single source of short-circuit current at one end. Cable should be reduced to the equivalent miles of overhead line as indicated in figure 10.

† When two sources of short-circuit current are available, the miles of line in column 2 should be increased by a factor K, determined from figure 11. If less miles of line between sources are available than required by the use of figure 11, but more than shown in column 2, then a detailed calculation is necessary for the application.

** Guide for application when minimum current is limited by resistance.

The minimum current rating which is assigned to standard protector tubes is based on the short-circuit current through the tube being limited predominantly by inductive reactance. The protector tubes will actually interrupt currents as low as 85 per cent of their minimum name-plate rating for circuits 69 kv and above or 70 per cent of their minimum current rating for circuits 46 kv and below, where circuit resistance (tube grounding resistance) is included, provided the calculated minimum current neglecting all resistance is equal to or greater than the tube's minimum name-plate rating.

sible severity of recovery voltages. It was recognized in selecting a suggested list of standard ratings that they would not cover all the possible applications. However, it was felt that a balance could be obtained between the circuit requirements and the design limitations of the protector tube which would cover the majority of applications. Weighing all factors, the miles of line listed in table II for each operating voltage were believed best suited. Lines shorter than those listed tend to give rise to more severe recovery-voltage characteristics than are generally encountered. With the system conditions listed in table II the corresponding recovery-voltage characteristics have been obtained from the studies already referred to and requirements for a protector-tube design determined so that the protector tube can operate and still have the dielectric-recovery curve above the system recovery voltage, or in other words, have successful operation of the device. Since rate of rise of recovery voltage immediately following interruption is essentially proportional to current, the significance of the first crests of the voltage-recovery characteristics is not as great for minimum current ratings as it is for maximum current ratings. Therefore, only one point is defined on the system recovery characteristics for protector-tube minimum current ratings while two points are defined for maximum current ratings. Since the majority of protector tubes are applied on solidly grounded-neutral systems, it was felt that this should be the basis for the standard design. Other methods of grounding will be dealt with either by the use of application factors to allow the selection of a standard protector tube for use on the special system or the design of a special protector tube.

Based on the above general thoughts, the following application guides are suggested for consideration in the standardization of this line of apparatus.

(a) Basis of Design

Protector tubes are designed to withstand one operation for tubes rated at 5,000 and 6,000 amperes, two operations for tubes rated at 3,000 amperes, and three operations for tubes rated at 1,500 amperes, at maximum rated current with fully offset current wave after which the protector tube will be required to clear two operations at minimum rated current and with the associated recovery voltage. The tube performance is based on interruption of the current actually obtained during the one test at maximum rated current in less than $^1/_{60}$ second and the minimum rated current in less than $^1/_{40}$ second.

The maximum symmetrical nameplate rating in table II is based on the maximum crest current which the tube will stand divided by a factor of not less than 2.5 to take into account the effect of asymmetry. The minimum symmetrical rms current rating is based on the minimum crest current divided by 1.41 to convert to rms amperes.

(b) Discussion of Standard Ratings

It is felt that the requirements set forth in table II are suitable for consideration for standard ratings. A review of the actual field experience with a large number of protector tubes indicates that although the tubes are designed for these very severe conditions, actual system conditions are very much less severe. For example, there are not many systems that have as few miles of line as the minimum selected. This means that recovery voltages on actual systems are generally less severe and therefore a greater number of operations or a greater amount of erosion is permissible. Likewise, the requirements are based on a completely offset wave with the low value of damping

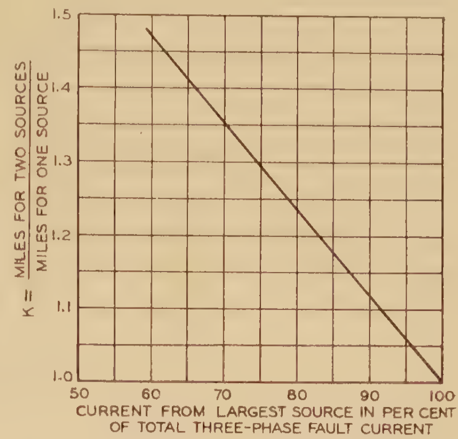

Figure 11. "K" factor for lines with two sources

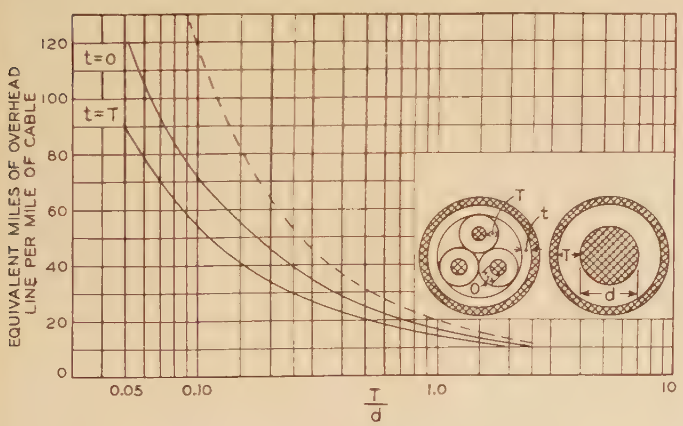

Figure 10. Overhead-line equivalent of cables

Dashed curve—Single conductor

Solid curves—Three conductors

For paper-insulated cable assumed dielectric constant 3.8

For varnished-cambric or rubber insulation multiply by 1.35

Overhead-line equivalent based on positive-sequence capacity, susceptance of 6.0 micromhos per mile

of the d-c component. The probability of securing the completely offset wave is low and also the damping on the actual system is usually higher than assumed. The rate of erosion is dependent on the magnitude of current. For example, a standard-design tube for a 34.5-kv system might have 25 mils erosion for each operation with maximum current completely offset as used for the design requirements whereas for minimum current it will take several operations before any similar erosion is found. Since tubes are applied for maximum system generation connected, any reduction in this item will reduce the short-circuit current when the tube operates and therefore reduce the rate of erosion.

(c) Standard Tubes Operating at Reduced Voltage

Where the minimum line-to-ground current of the circuit is below the minimum current rating assigned to standard tubes, and the insulation of the circuit is high enough to permit the use of a tube having the next higher voltage rating, this higher-voltage protector tube will interrupt lower than the listed minimum current.

To determine the minimum current which the protector tube will interrupt when used on a circuit below its voltage rating, multiply the normal minimum current rating of the protector tube by the ratio of the lower operating voltage on which the device is to be used to the normal voltage rating of the protector tube. This lower value of current can

be considered as being limited by reactance only and applied in the same way standard tubes are applied.

Conclusions

In view of the large amount of analytical work and the eight years of field experience with protector tubes, all of which has been taken into consideration in the preparation of this paper, it is recommended that the information contained in this paper be considered in conjunction with the proposed protector-tube standards as a basis for their application.

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Discussion

M. C. Westrate (The Commonwealth and Southern Corporation, Jackson, Mich.): The paper covers the installation of protector tubes on transmission lines only, and does not mention their use for station application. We believe, however, that there is a definite application for protector tubes on line entrances to substations for protection of air switches and oil circuit breakers in open position. The simplicity with which these tubes can be installed has made it possible for us to install them for less cost than plain rod gaps in some cases. We have carefully engineered all our applications of protector tubes, and the experience has been very satisfactory both on 44-kv isolated-neutral and 22-kv grounded-neutral systems. We are now installing some at stations on a 140-kv grounded neutral system.

On the isolated-neutral system, we have used only the three-tube scheme with tubes of the same rating as for a grounded-neutral system. The problem on isolated neutral systems is usually that single line-to-ground faults do not produce enough current for satisfactory expulsion action of the tubes; however, if the system is not too large, the current may be low enough to interrupt itself without this action.

It was indeed a surprise to learn that protector tubes should be designed for such a limited life as one, two, or even three operations. A further explanation of this would be appreciated since it does not agree with other published information. Even for transmission-line application, where the number of operations would not be as many as for station use, this does not seem to be a reasonable life to use as a "basis of design".

It would also be very desirable to have published data in the form of curves on the volt-time breakdown characteristics of protector tubes. This is covered to a limited extent in figure 6 but is not complete enough to cover application in connection with switch-type insulators or bushings.

Several places in the paper mention is made of the discharge voltage of the tube whereas it is believed that "breakdown voltage" is intended. This is a minor point but may be confusing since in lightning-arrester work, the discharge voltage is usually considered as the *IR* drop after breakdown.

I. W. Gross (American Gas and Electric Service Corporation, New York, N. Y.): Knowing how a device is intended to function and the conditions under which it should be applied in practice are very helpful in studying the performance of the device itself when subject to operating conditions.

On the American Gas and Electric Company's interconnected 132-kv system, we have at the present time over 3,000 protector-tube assemblies installed on each phase conductor at each tower of six separate transmission lines varying in length from some 35 to 67 miles. Before these tubes were installed, staged field tests were made on tube designs to determine their suitability for interrupting power current. The initial tests made in 1932, were carried out on that part of the system where the maximum symmetrical rms short-circuit current was approximately 4,000 amperes. Further staged tests were made two years later on part of the system where the short-circuit current ran up to 10,000 amperes. It is interesting to note that when both of these tests were made, the problem of rate of voltage recovery rise of the system was not even considered. When these tests were made, the tubes were subjected to currents far exceeding the rated current which the design had predicted they were capable of interrupting. The point I wish to make here is that theoretical and design considerations must be co-ordinated with practical experience before the ultimate limits in performance of any protector device are known. From our experience in operating a large number of protector tubes in actual service during the past seven years, we have yet to find any indication that the tube has been subjected to power system current outside of its rating. The fact that our 132-kv system, being interconnected, far exceeds the 90-mile line length, indicated as a minimum by the authors in table II, indicates that we are not concerned with limits of line length in this particular application.

A considerable number of other installations on lower-voltage lines where protection has been undertaken on disconnecting switches, cables, and reactors, have operated satisfactorily from the point of view of tube rupture. On the basis of our experience with the application of protector tubes during the past seven years, we are wondering whether there is any evidence outside of theoretical considerations which indicates that the line length is such an important factor as the authors seem to stress in the paper. The problems which we have encountered in applying tubes may be summarized briefly as follows:

1. Ability of the tube to withstand weathering.

2. External tube flashover under lightning conditions. The record shows a decrease from approximately 11.4 per cent of flashed over tubes of the initial design to 1 to 1[1]/2 per cent on the newer designs. This problem seems to be reasonably under control.

3. As pointed out by the authors, the relay time setting must be sufficiently long to permit the tube to function without breaker operation. We have set a limit of about two cycles as a practical lower limit. Where high-speed breakers are installed to minimize conductor burning, line troubles, and for better system stability under fault conditions, the necessity of introducing longer relay times tends to undo the benefits possible with high-speed breaker action if this time delay is too great.

4. The disposal of ionized gases when the tube is operating appears to be a problem which should be given careful consideration particularly on tube application on the lower-voltage circuits where the conductor spacing is low. This consideration should be carefully watched, not only from the point of view of disposal of the gases from the tube vents but also from the viewpoint of possible traveling of the arc at the open gap end of the tube which may develop an arc on insulators or other closely adjacent equipment.

There is at the present time work being done in setting up a standard for protector tubes under the sponsorship of the lightning arrester subcommittee of the AIEE Protective Devices Committee. This work is now in second draft form, and this present paper, as well as the discussions which may be offered here, will be helpful in carrying on this work to a completion.

While it is not clear from the paper whether the authors are proposing that their table II be incorporated as a part of these standards now in progress, it is doubtful whether too much specific limitation should be placed on *tube standards* to the point where development in the device itself may be hampered.

F. E. Andrews and **H. A. Cornelius** (Public Service Company of Northern Illinois, Chicago): Although the probability of having sufficient lightning-stroke current to damage a protector tube is small, as indicated in the paper, such a failure occurred in the past lightning season on the Public Service Company of Northern Illinois 34.5-kv system. This 1,200 to 10,000-ampere tube had been in service just 14 days.

One disturbing point noted in the paper is the recommendation that where protector tubes are used, the high-speed-relay time should be at least two cycles. This is unpleasant news since it means adding external devices to decrease the effectiveness of such relays. If a tube should fail to clear after the relays have been slowed down, the fault might be on the system at least three cycles longer than at present.

Since the experience on which this recommendation is based is not given, an investigation was made of 34.5-kv lines on which protector tubes are installed in the instantaneous zone of the high-speed relays and of the line tripouts which occurred in the past lightning season.

The data are as follows:

Number of relay operations known to be due to tube operation 2
Number of relay operations probably due to tube operation 4
Number of known tube operations unaccompanied by relay operation 6

Included in the "relay operations probably due to tube operation" group are all otherwise unexplained line tripouts, so this figure may be high. Also, there is no practical way to determine the total number of tube operations. Therefore, the number shown as having occurred without causing relay operations is undoubtedly lower than it should be. Although these data are not conclusive, it indicates that using one-cycle relays has caused few unnecessary circuit outages.

The next point to be discussed is that accidental closing of the required external series gap has caused five tube flashovers with line interruptions resulting. The problem of holding the gap within the prescribed limits points to the need for further improvements. Is it practical to include the "series air gap" now used integral with the tube?

In regard to the protection provided, the statement is made that "where the protector tube gives protection to an insulator on a positive 1.5x40-microsecond wave at the critical flashover point, the protector will in general also protect for waves rising to flashover in shorter times or on negative polarity." The basis for including negative-polarity waves, which are about 15 per cent larger in magnitude than positive waves, within the protection provided by the tube, is not clear. The hyperbolic volt-time characteristic of insulation is apparently the basis for the protection provided by the tubes on steeper front waves than 1.5 microseconds.

Since successful operation and tube life vary with the degree of erosion of the tube walls and since the erosion to be expected at these widely separated tube installations would be greater than on lines having tubes on every pole, measurements of the erosion in 80 tubes were made. The data on the service life of these 80 tubes, erosion measured compared to years of service, etc., are given in table I of this discussion. Although the data are not very extensive, they are considered a representative sample for tubes in service for three years or less and indicate that severe tube erosion is rather uncommon.

One of the reasons given for the proposed standardization of protector tubes is that eight years of experience has been obtained

Table I

Number of Lightning Seasons Tubes in Service		Erosion Measured		
Years in Service	Number of Tubes	$^{1}/_{16}$ Inch	$^{1}/_{32}$ Inch	0 Inch
3	30	2		28
2	41	3	7	31
1	9		1	8
	80	5	8	67*

* Twenty-one of these tubes showed arc scars, etc., indicating that operation had occurred. The remaining 46 tubes probably had not operated.

with this device. Although in the past two years a much better understanding of protector-tube characteristics and of the effect of system characteristics on tube operation has been obtained, there still remains a question as to whether this device is ready for standardization. The basis for this questioning is the frequency with which troubles are encountered with this device. In support of the preceding statements, the experience with 196 three-phase sets of protector tubes, which have been installed at widely separated locations, in the past six years on the 1,100-mile 34.5-kv system of the Public Service Company of Northern Illinois may be cited.

1. Nineteen tubes failed apparently from the generation of excessive internal forces. Eight of these tubes were found destroyed after lightning storms and portions of the tubes were scattered 200 feet away. The other failures are not clear-cut as to cause, but it has been established that the failures were not due to erosion of the tube walls nor to having fault current flow less than the tube rating.

2. Practically all of these 19 tube failures have occurred in the past two years at seven different locations. Sixteen of the tubes have failed at four locations at various times. The number of tubes in service by ratings and the failures to date are as follows:

Tube Current Rating	Number in Service	Failures to Date
200–900	18	0
600–2,500	3	0
900–5,000	156	3
1,200–10,000	66	5
400–4,250	36	6
250–3,500	270	0
400–3,000	27	0
700–3,600	12	3
Unknown	2	2
	588	19

Another point of importance is the probable life to be expected of these proposed new standard tubes. Although the discussion on the basis of the design states that a 6,000-ampere tube is designed to withstand only one operation at maximum rated current when the current wave is completely offset, the discussion on the standard ratings of the tubes implies that more than one operation may be expected under service conditions. Unless the probabilities indicate considerably more than one successful tube operation in service, the new design does not appear practical. It is believed that effort should be made to provide tubes which will operate in service for a reasonable number of times. It is also believed that the tubes should be rated on the basis of expected field performance rather than on the basis of test performance. Such test performance appears widely divergent from typical operating conditions.

There are two points in connection with the proposed standard tube ratings: one has to do with a larger current rating than given in table II and the other with the reasons explaining why the physical length of the tube has been increased but the rating of the tube decreased.

1. At locations where 8,000 to 10,000 amperes short-circuit current may flow, none of the proposed standard tubes could be used, for the maximum current rating given is 6,000 amperes. The service experience at such high fault current locations where 1,200 to 10,000-ampere tubes have been in use for three to six years has been satisfactory. Pole-top switch insulator flashovers have been eliminated where tubes are installed, and there appears to be a general improvement in line performance. Unfortunately, the number of protector tubes in service by years is not available; but the average failure rate is estimated to be less than three per cent per year. In our opinion, the 10,000-ampere tube should be included in the proposed standard ratings.

2. Published data on the new standard protector tubes show them to be longer in the 34.5-kv class than before the change in rating by from one to four inches. This increased length should permit increasing the internal gap and thus the maximum 60-cycle voltage the new tube can clear after an operation, as well as the range of power current that can be interrupted at 60-cycle voltage. Instead, the new standard protector tubes are rated at approximately half the current interrupting capacity previously used. That is, on the old rating a 17-inch tube was rated 1,200 to 10,000 amperes, whereas on the new rating a 23-inch tube is rated 600 to 6,000 amperes. This seems to be a step in the wrong direction from the user's point of view, and the justification for such a marked change in tube rating is not apparent.

Two subjects considered of general interest are (1) some of the difficulties experienced while learning to install the tubes properly and (2) a description of two types of tube failure which have been observed.

1. Improper installation has caused trouble with about 25 tubes. The most common types of difficulty were due (*a*) to mounting the tubes on insulation having lower flashover values than the tubes, which accounts for about half the trouble experienced; (*b*) to flashover resulting from accidentally shortening the external gap; (*c*) to having the discharge gases directed so as to cause flashovers on adjacent equipment; and (*d*) to having insufficient clearance between the tube and the insulator it parallels.

2. The cases of tube failure due to power system current were generally characterized by an irregular parting of the tube fiber just above the metal base fitting which was attached to the mounting bracket. The bore of both the fiber and the base fittings had enlarged considerably. The erosion of the metal in many cases was approximately equal in amount to that of the fiber. One tube which had not failed was found with this same type of erosion, the bore having enlarged from $^{3}/_{4}$ inch to $^{15}/_{16}$ inch. This was located on a pole adjacent to one of the tubes which had failed and was thus presumably subjected to similar conditions.

On the other hand, in the case of the failure diagnosed as due to lightning stroke current, the tube was not appreciably eroded; and the fiber had parted at the metal base fitting with a relatively clean break.

While much of this discussion may seem to be devoted to tube shortcomings, we wish to point out that in over-all performance our use of tubes has been generally successful; and through their use, a definite reduction in certain types of lightning troubles has been accomplished.

C. Concordia (General Electric Company, Schenectady, N. Y.): From table II and the discussion under it, it might be inferred that protector tubes should be specified for proper operation on circuits having at least the required equivalent line length. However, I do not believe this is the authors' intention, or that such a specification is desirable. Instead, tubes should be specified for successful operation within their current rating and for recovery voltages no more severe than those listed in the table. That is, mere satisfaction of a certain system condition should never logically be taken as the fundamental requirement of any interrupting device; instead, it must be decided whether or not the permissible current ranges or recovery

voltages are exceeded, the line length serving as a guide to this decision. Thus, the information given in this table should be of considerable assistance in assuring proper application of tubes.

A. C. Gohlke (Cleveland Electric Illuminating Company, Cleveland, Ohio): This paper gives a clear outline of the many variables to be considered in the application of protector tubes to a given power line and the standardization of protector-tube designs would facilitate the correct tube applications to a great degree.

Our experience with protector tubes of the 34.5-kv class has indicated the following:

1. Tube failures from excessive impulse discharge currents have been most common. Shattered tubes have been found in the 5,000-ampere class as well as the 1,500-ampere class.

2. External flashover of tubes has occurred in a number of instances, indicating high impulse discharge currents or insufficient margin of external insulation over internal-gap breakdown.

3. Several cases of insulation failure of tube walls have occurred showing path of dynamic current from internal electrode through wall of tube to external ground.

4. Tubes have continued to clear successfully after repeated operations at locations of approximate minimum current values.

5. External finishes on tube walls have not been effective for more than three to five years.

R. J. Patterson, R. R. Schump (nonmember), and **E. H. Grosser** (nonmember; all of Commonwealth Edison Company, Chicago, Ill.): It seems to us that, with one or two exceptions, the paper covers the subject very thoroughly. Our only difficulty was in co-ordinating the various factors dealing with protector tubes, and we are of the opinion that a more straightforward presentation would help when and if this information is written into standards.

Enlarging on this matter, it would appear preferable to separate design factors from such application factors as system characteristics, lightning severity, anticipated life, and installation and maintenance methods. Incidentally, we should like to see someone from either of the manufacturing companies present a discussion of this paper giving up-to-date information on electrical connections, various methods of installing protector tubes on lines of various types, relative protection to be expected with different arrangements and numbers of tubes per phase per mile, and methods of mounting the devices on structures. We should also be interested in a discussion of the limitations of these devices in protecting inductive and possibly capacitive apparatus, which was not covered in the paper.

A few specific comments on the paper are given below:

1. In tables I and II, it is not clear that the circuit voltage rating is also the voltage rating of the protector tube. Also, it is difficult to tell whether the columns 2 and 3 values for discharge critical voltage do or do not include the recommended series gap. If they do, then the voltages corresponding to the protected arcing distances shown are more than ten per cent greater than the tube discharge voltage as stated in the second paragraph under "Protector-Tube Characteristics." We wondered if tolerances for erratic discharge voltages were also added to the tube discharge voltages shown. Along this same line, it would be interesting to know whether the series capacitances of the tube and external gap are such as to prevent a cascading type of discharge, in which either the tube or gap operates first. If this did occur, the voltage existing across the combination would probably be limited to the discharge voltage of the tube alone.

2. Under item (*e*) of the section on "Protector-Tube Characteristics" it would be of interest to learn to what extent the impulse and power-frequency characteristics of tube and external gap are affected by rain, humidity, and dirt.

3. Does figure 7 apply to all ratings of protector tubes?

It may be of interest to learn of our experience with the revised installation of protector tubes on a 33-kv wood-pole line. This line, which is about three miles long, has two conductors spaced nine feet on a wood crossarm and the third conductor mounted on the ridge pin, five feet nine inches above the plane of the other two conductors. The first two years of operation, with no protector tubes installed, was unsatisfactory, three cases of lightning trouble occurring in 1936 and eight in 1937. Then protector tubes were installed on all three phases of the line, but spaced about ten spans apart. Seven cases of lightning trouble occurred with this arrangement in 1938. As a result of this operating experience, it was decided to modify the protective installation to provide one protector tube on the top conductor only on every pole throughout the line, except that three gaps were installed on corner poles and such few poles as have flat configuration. Ground resistances were reduced to a value which calculations indicated would prevent flashover voltage between phase wires being attained with severe stroke currents. With this protective scheme in operation during the entire 1939 lightning season (which, however, has not been an unusually severe one), no lightning troubles or outages have occurred on this line to date. Although the minimum and maximum ratings of the tubes were raised for a portion of the line, the improved performance is attributed to the manner of locating the gaps on the poles.

Our comments on the standardization portion of the paper are as follows:

The proposed standard line of tubes as given in table II, taking into consideration the application of a standard tube at reduced voltages, should suitably cover requirements of various systems. The basis of design, namely, one, two, or three operations at maximum rated current with completely offset wave for the 1,500, 3,000, and 5,000 to 6,000-ampere tube, respectively, seems to give little assurance of realizing a fair amount of protection for the investment in tubes and their grounds. The tentative selection of 1,500, 3,000, and 5,000 to 6,000 amperes for maximum rating indicates that some overlapping of currents is permissible for successful operation; otherwise a larger number of tubes should be required to adequately cover line conditions. If this is true then it would seem that a 3,000-ampere tube, for instance, could be expected successfully to withstand more than two discharges at 3,000 amperes with completely offset wave.

It would seem desirable to incorporate in the paper some indication of the number of operations which can be expected from a tube for the most severe, average, and least severe conditions assuming the tube grounding resistance to be zero.

Some mention might also be made of standardization of mountings so that a tube of one manufacturer could be replaced, if desirable, with a tube of another manufacturer without replacing the bracket.

As the tube rating is appreciably affected by the bore diameter, it would be desirable from the user's standpoint to have the nominal diameter stamped on the name plate. This would assist in determining when a tube should be replaced. Also, the construction should be such that the bore can be readily determined by measurement in the field.

A. D. Forbes (Westinghouse Electric and Manufacturing Company, Sharon, Pa.): This paper has been limited by its authors to the field of the type of protector tube which is used for the protection of transmission-line insulation. There is also the type of deion protector usually referred to as a "deion gap" which, to date, has been used principally for the protection of distribution-transformer windings. It may be well to point out the similarities and differences of this type of equipment.

The deion gap operates on the same principle as the protector tube—deionization of the power arc by means of gas generated by decomposition of fiber by the arc.

The deion gap differs from the protector tube in two respects, however. First, the deionizing section of the deion gap consists of a number of parallel slots instead of a cylindrical hole as used in the protector tube. The slotted construction allows the two opposite walls to be close enough together that there is no minimum power current which the deion gap will interrupt—it will clear from zero amperes upward.

Second, series resistors are normally used with deion gaps. The series resistor limits the power follow current regardless of the short-circuit current of the system. There is therefore no maximum current which can be interrupted and the deion gap can be applied universally to any power system.

Data which have been presented by Hodnette,[1] Ludwig,[1] Bellaschi,[2] Sporn,[3] and Gross[3] indicate that the probability of a 50,000-ampere surge each year is 0.23 per cent to 3.7 per cent. More recent experience with deion gaps in transformers on distribution circuits indicates a probability of about 0.9 per cent for 50,000 amperes, and 0.1 per cent for 100,000 amperes. Experience gained indicates that gaps for transformer application which can successfully discharge a surge of 100,000 amperes decreasing to half value in 50 microseconds are satisfactory. We note that the surge-current capacity of the protector tube, as mentioned under "Protector-Tube Characteristics" is 50,000 to 100,000 amperes for a duration of 20 microseconds to half value. For applications where protector tubes are used, there are possibly more parallel paths for lightning to drain off to ground and possibly because of this, the high surge-current capacity of the deion gap, for transformer application, is not required by the protector tube for line application.

References

1. Surge Protection of Distribution Systems, J. K. Hodnette and L. R. Ludwig. Electrical Engineering (AIEE Transactions), June 1937, page 683.

2. Lightning Currents in Field and Laboratory, P. L. Bellaschi. Electrical Engineering (AIEE Transactions), August 1935, page 837.

3. Lightning Currents in 132-Kv Lines, Philip Sporn and I. W. Gross. Electrical Engineering (AIEE Transactions), February 1937, page 245.

H. A. Peterson, W. J. Rudge, A. C. Monteith, and L. R. Ludwig: The discussions presented on this paper are very encouraging to the authors as they not only bring out factors that were not included in the paper but also give very valuable operating experience on the device under discussion.

Referring to the discussion by Mr. Westrate, the authors wish to point out that the demonstration tests proposed cover extreme conditions which are very unlikely to exist in the actual application of tubes to power systems. In the first place, in actual operation numerous factors affect the magnitude of the short-circuit current which will be passed through the tubes; that is, the point on the wave at which lightning strikes, the offset factor in the first cycle of current flow, the reactance of the lines, etc., will usually result in a peak current through the tube which is lower than the maximum current called for in the test. The resultant effect is in the direction to give less erosion, or in other words a greater number of operations.

In the second place, it should be recognized that usually it is the minimum current which dictates whether or not the tubes will clear. It is very likely that in actual practice the minimum current of the system will be above the minimum rating of the tube, and the system recovery voltage will generally be less severe. As the result of this influence the tubes are capable of a greater number of operations before the tube bore erodes to the point where the tubes will fail to clear properly. There have been many cases pointed out in the literature and in the discussions presented before the AIEE where tubes have operated numerous times without reaching the end of their useful life. It is our feeling that the proposed test can be used only in a comparative sense. The actual number of operations can be determined only from experience with the tubes in the field.

We are in agreement with the thought expressed that the protector tube can serve as a secondary protection device. It will serve to protect line insulators, disconnecting switches, and the like. However, we wish again to call attention to the fact that we would expect tubes used in this fashion to have a shorter life from the standpoint of erosion than tubes used to protect every structure along the transmission line. This would be particularly true in cases where the protector tube is attached to a station which is fed by a highly insulated line, as practically all strokes in the vicinity of the station will cause operation of the tube, if the oil circuit breaker or pole-top switch were in the open position. Naturally, tubes used for this purpose would have to be replaced more frequently than in cases of normal application. It is entirely possible that additional tubes for, say the first two or three structures out from the station, would divide the number of operations in such a way as to prolong the periods required between tube inspections.

Some of the principles used in this device are incorporated in a tube for the protection of all apparatus in the voltage classes 15 kv and below. There are features included in these tubes, however, that are not incorporated in the tubes discussed in this paper and their standardization should be considered separately. We were particularly interested in the comments on the application to free-neutral systems. It will be of interest to again review this experience in the course of two or three years. It is quite possible that too conservative a point of view is being taken in regard to the application to free-neutral systems.

The volt-time curves Mr. Westrate refers to are available in published literature of both manufacturers. In making use of them, one point should not be overlooked. The laboratories of the manufacturers are able to check each other with a very close degree of accuracy on $1^1/_2$x40-microsecond critical flashover tests. However, there are discrepancies between laboratories on values obtained for breakdowns at short times in the region of one-half microsecond. Therefore, in making an application, volt-time data for protector tubes obtained in one laboratory should be compared with volt-time data for insulators obtained in the same laboratory.

Mr. Westrate questions our use of the term "discharge voltage", stating that he believes breakdown voltage is intended. We agree that there is need of clarifying both the terms and their definitions. We feel that this can best be done by the AIEE committees who are at present writing standards for the tubes, and we are referring this matter to the proper committees.

Mr. Gross points out that miles of line are not of particular concern to him in the application of tubes, since their minimum miles of line far exceed the 90-mile minimum required in the paper for 138-kv tubes. This is undoubtedly true while the system is interconnected. However, there may be operating conditions in which a portion of the 138-kv system is disconnected and this portion may have less than the 90 miles required in which case the recovery voltage will be more severe with corresponding risk of tube failure. Such conditions probably correspond to emergency conditions and not conditions that will normally exist on the 138-kv system. This is just another way of saying that tubes will be capable of a larger number of operations under usual service conditions as pointed out before.

It is true that in the case of the system cited by Mr. Gross miles of line or the corresponding recovery voltages are not major factors. However, there have been numerous other cases in which the length of line or severity of the recovery voltages have been of major importance in the application of tubes.

In connection with the question of how important length of line is in determining the recovery characteristics, tests have been made not only on the miniature transient analyzers referred to in the paper, but in the field as well. These tests show definitely that the recovery characteristics are affected by miles of line. It should be thoroughly appreciated, however, that the miles of line given in table II are purely to serve as a guide for application and it was not the intent to use miles of line to specify tube characteristics. This also applies to Mr. Concordia's discussion. The tube characteristics should be stated in terms of the recovery voltage characteristic for which they are designed, and it was our intent to do this in specifying these characteristics in the paper.

We agree with the thought suggested by several discussers that the slowing up of high-speed relays introduces another complication, and from this point of view, an unfortunate one. However, a line properly equipped with tubes should normally not require the operation of the relays. This represents a definite improvement in performance both from the standpoint of increased stability and from the standpoint of a decreased amount of conductor burning. In the possible event of a tube failure to operate, or in cases where insulator flashover cannot be controlled by the tube, such as might occur with an accumulation of dirt or the like on the insulators, the two cycles, in general, will not appreciably change the amount of burning nor affect the stability.

The operating experience outlined by Mr. Gohlke is of interest in connection with the performance of the device under discussion. We believe, however, that the tubes in question are of special design to meet special system conditions, and not tubes designed for general application such as are being considered in this paper.

In answer to the discussion by Messrs. Patterson, Schump, and Grosser, it should be pointed out that the factors affecting the different distributions of protector tubes along the line have been analyzed and presented in the literature. We refer to "Protection of Transmission Lines Against Lightning—Theory and Calculations" by L. V. Bewley, *General Electric Review*, June 1937.

With regard to the question of electrical connections and methods of mounting, we believe that both manufacturers' bulletins show typical mounting arrangements and methods of connections and by referring to these publications, this information can be obtained.

With regard to the question of protecting inductive and capacitive apparatus, the question is not clear to us as to just what was intended. However, we believe that our comments on Mr. Westrate's discussion answer this point.

With regard to item 1, the voltage rating contained in table I and table II is the tube circuit-voltage rating. The nominal voltage rating of the tube is the maximum permissible continuous rms voltage across the tube assembly, including the series gap, and is at least the circuit voltage divided by the $\sqrt{3}$. The impulse values given in table I include the listed series gaps appearing also in table I.

With regard to item 2, the extent to which the breakdown characteristics are affected by rain can be determined for standard rates of precipitation, but there appears no practical way of determining the effect of humidity and dirt, as these factors will vary so widely with different localities that it seems impractical to evaluate them.

With regard to item 3, figure 7 of the paper is typical of the characteristics of all protector tubes, although the specific values given apply only to one particular tube, and one particular voltage rating. This curve was included to show how, in general, the recovery characteristics of the tubes

Modernization of a Transit System—Factors That Determine the Choice of Vehicle

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THE transit industry is facing serious economic problems. Shrinking revenues, due largely to the competition of the private automobile, and increased operating expenses have together so decreased the margin between income and expenses that many systems are now in financial straits. The best solution for these problems, so far advanced, is to modernize the equipment and rehabilitate the service. Some lines have already been modernized; most of the remainder badly need modernization. Present equipment is old and expensive to operate; the service is slow, infrequent, and generally unattractive to the riding public. Through substituting new, fast, comfortable vehicles, run on frequent headways, for the present obsolete equipment and through aggressive management, most transit systems, if not all, may regain a considerable portion of their lost traffic and thus get back to a more satisfactory financial condition.

Most city transportation systems were originally equipped with street cars, because at that time the street car was the only transit vehicle known. At present, in a well-planned modernization program, two additional vehicles, the trackless trolley, or trolley bus, and the gas bus, merit consideration.

Even engineers and operating men disagree as to the relative merits of the three types of vehicles. There are "street-car enthusiasts" and "bus enthusiasts", while still others believe that all three may have a legitimate place in a modern transportation system. In view of the large expenditures involved in even a very modest modernization program, these differences of opinion make appropriate at this time some explanation of the basic factors governing the choice of vehicle, a selection that should be based, as far as possible, on facts rather than on personal preference for a particular type of conveyance.

The purpose of this study is twofold: first to show the application of the engineering method to the problem of selecting the most suitable vehicle with which to modernize an existing transit line; and second, to determine as nearly as possible, for average conditions, the range of traffic volume within which each vehicle is most economical.

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Requisites of a Modern Transportation System

A modern transportation system should fulfill three fundamental requirements. These are: first, it should render adequate service; second, the vehicle used should be attractive to its patrons; and third, the over-all cost of operation should be the least practicable in order to make a low rate of fare possible. The three types of vehicles will next be compared with respect to those qualities most essential to a modern transportation system.

First, Adequate Service

The principal factors that determine the adequacy of service, from the patrons viewpoint, are safety, frequency of service, accessibility, and speed. Of these the first is the most important.

Safety. Because the street car follows a pair of rails, in case of icy streets, foggy weather, or other unusual conditions, it may be expected to follow a definite fixed route. Rubber-tired vehicles must be steered, and hence under such unusual conditions are at some disadvantage. However, experience has shown that, given proper operating methods, such as the use of chains, and the sanding of slippery streets, these hazards can be reduced to a minimum.

With street cars, passengers must board or alight from the cars in the middle of the street, but with the rubber-tired vehicles loading takes place at the curb. Curb loading has the advantage that it is less dangerous for the patron because he is not forced to pass through vehicular traffic in order to reach the public conveyance.

Frequency of Service. In the eyes of the public, frequency of service probably has a greater bearing on the quality of a transportation service than any other

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would vary as a function of the current passed through the tube.

With regard to the question of standardization of mounting fitting, also of stamping the tube's original diameter on the name plate, we are referring these matters to the proper committees.

Messrs. Andrews and Cornelius bring out a point that is too often overlooked. The length of series gap given in the paper is based on obtaining the performance given in the tabulations. If the insulation of the systems is high then the series gap can be increased minimizing the necessity of careful setting of the series gap. These gentlemen have also given very valuable operating data which will be of interest to the art as these data show that in actual practice more operations can be obtained than outlined for the demonstration test.

We have noted with particular interest the operating experience of tubes reported by Messrs. Andrews and Cornelius. However, we wish to caution against comparing these data with the data presented by Messrs. Gross and Sporn, for it is our understanding that in most of Mr. Cornelius' and Mr. Andrews' cases, tubes have been installed on pole-top switches and isolated structures, whereas the figures given by Messrs. Gross and Sporn are for cases where tubes were installed on every structure along the entire length of line. As pointed out in answering Mr. Westrate, tubes located at terminal structures or guyed structures and located intermittently along the line, will be subjected to a greater number of operations than tubes located on each structure along the line, and for this reason will have a shorter life.

The authors feel that it is very desirable to have a standardization at the present time as this allows starting with a common basis. This will provide a method of making a comparison of the performance of devices for any system. We should not, however, lose sight of the fact that if the basis selected for standardization at the present time is not correct then it certainly can be changed when this fact is established. It should be recognized that the physical length of the protector tube does not determine the rating. Rather, this is dependent on the actual space between internal electrodes, bore, and wall strength. Too much stress should therefore not be placed on the physical dimensions of tubes having different current ratings but the same voltage rating. It should be expected as a result of this standardization that more uniform tube designs will result with a greater reliability of operation.

single factor. The modern automobile has taught the public to expect from its transportation system accommodation in a measure approximating in convenience the house-to-house service of the automobile. Unfortunately cost is a limiting factor. The best that can be done is to render as frequent service as possible, with the smallest vehicle practicable to operate within the economic limitations.

Accessibility. Of almost equal importance with frequency of service is accessibility. Formerly the common practice was to space transit lines almost a mile apart. The patron walked, not from choice but of necessity, the half mile to the car line. With the advent of the automobile, an increasing percentage of the population refuses to walk this distance. Experience has shown that where the walking distance is much over a quarter of a mile, or where the service is too infrequent, the public will begin to use other forms of transportation.

This situation may be handled in three ways. One is to space the lines more closely together. This method has the disadvantage that unless the population is very dense, the traffic on all lines will be so light that it is economically impossible to give frequent service on any of them, even with small vehicles. A further disadvantage of this method is that the large number of small vehicles that would be required leads to congestion in the metropolitan areas. However, this may not be as great a limitation as might at first be supposed. The private automobile now on the street carries on the average approximately $1^3/_4$ persons per car. If the use of small vehicles on closely spaced lines would attract back to the public transportation system any considerable number of people that would otherwise use their own cars, the results might well be a decrease in traffic congestion.

The second possibility is to use small vehicles, usually busses, as feeders, transferring the passengers to a few trunk routes, on which the traffic will be heavy enough to warrant frequent service with larger and more economical units. The disadvantage of this plan is that a large proportion of the passengers must transfer.

A third method is to use a terminal system,[1] as that proposed by A. V. Eastman, in which all lines from the outlying districts terminate in two or more terminals located near, but still outside, the metropolitan area. Heavy trunk-line service is provided between these terminals, over several alternate routes so spaced as adequately to cover the metropolitan district.

Speed. Much of the appeal of the private automobile, aside from its convenience, is due to its superior speed. Although speed is important in a transit vehicle, it must not be attained at a sacrifice of safety. Owing to the large number of stops which it must make, no public conveyance in use on city streets will ever be able to equal the speed of the private automobile. A high schedule-speed (by schedule-speed is meant the average speed including all stops, layovers, etc.) is desirable for two reasons; first, it speeds the passenger to his destination, and second, it reduces the cost of giving service. Costs are reduced because both the number of cars required to run a given service and the amount of platform labor are decreased.

The schedule-speed of modern transit vehicles is much superior to that of their predecessors. For example, the Presidents Conference Committee car, usually called the PCC car, is designed to have a schedule-speed, on level track, of 14 miles per hour with eight seven-second stops per mile. The trackless trolley as far as acceleration, etc., are concerned is equally good. The gas bus, because of its limited power supply, and, if it is of the mechanical type, the necessity for shifting gears, is definitely slower than either of the other two; particularly if the number of stops per mile is large. This is one of the factors that makes the gas bus better suited to lines of light traffic, where the number of stops will be low.

The gas bus has a considerable advantage over both the other vehicles, in that, because it does have its own power plant, its route is not restricted to that of an overhead trolley. In times of emergency or even under normal[2] conditions this may be a very valuable asset. The self-contained power plant also makes possible both local and limited or express service on the same street without additional complications or investment. This double service is also made possible with the trackless trolley by use of either an auxiliary turnout in the overhead at the overtaking point, or of double overhead; either equipment requiring some additional investment. With street cars it is not feasible to operate both local and express service on the same street.

Second, Attractive Properties of Vehicle

The private automobile has made the public more critical than formerly of its transit vehicles. In order to attract patronage the vehicle used should be comfortable to ride in and reasonably quiet in operation, and should be convenient to board and alight from.

Comfort and Quiet. In all of the new vehicles, regardless of type, much more attention is now being given to comfort and quiet. Seats are upholstered, and by an ingenious use of rubber in both running gears and body, the noise has been greatly reduced and the riding comfort improved.

Convenience. Because of curb loading, in convenience of ingress and egress, the advantage is very much in favor of the rubber-tired vehicles. The principal disadvantage of curb loading is that it may necessitate establishment of loading zones at the more important points, especially in business areas. To be effective, these zones must be kept clear of parked automobiles, so that the transit vehicle may draw in to the curb to pick up or discharge passengers.

Third, Cost

In general, operating costs vary with both the size and kind of vehicle. For a given type, the operating cost per vehicle mile is less for a small conveyance than for a large one, but the cost per passenger mile is just the reverse. For a unit of given size, the gas bus requires the smallest capital investment, but has the highest operating cost (exclusive of interest and depreciation) of the three. Consequently it is best suited to lines of light traffic where the higher operating cost per mile is more than compensated for by the lower fixed charges on the smaller investment required. Hence, at light traffic volumes it yields a larger net return, with better headways and a smaller capital investment than would be possible with either the trackless trolley or the street car. The street car is best suited to very heavy mass transportation, where the traffic is heavy enough to require a large unit and is able to support the charges on the extra investment in track. Hence, with very heavy traffic, the street car, because of its larger size and lower operating cost per passenger mile, yields a greater net return, with entirely acceptable headways, than would be possible with either the trackless trolley or the gas bus, and this in spite of the large investment required for the track. The trackless trolley is intermediate between the other two, both in operating cost and investment.

As in any other business, in order for a transit system to continue as a going concern, its income must exceed, by a reasonable margin, its expenditures. Un-

1. For all numbered references, see list at end of paper.

fortunately, this has not been the case in the transit industry, as a whole, for many years.

Two methods for remedying this deficiency have been tried. The first is to increase the income by increasing the rate of fare; the second is to raise the net income by improving the service so as to attract more patronage, at the same time reducing the cost of operation per passenger.

The efforts to increase the income by increasing the rate of fare have not been uniformly successful; in fact, in some cases where fares have been increased the resulting decrease in traffic has very largely offset the effect of the fare increase.

The second method, that of increasing the net return by improving the service, is much to be preferred. The most effective way of improving the service, and at the same time holding down costs, is to modernize the system by replacing old equipment with new vehicles properly chosen to fit the traffic conditions of each individual line.

So far as the author is aware, in all cases where a well-planned modernization program has been put into effect, the results have been better than were anticipated.[3–6] In addition to operating at reduced cost, the new vehicles have won and held increases in traffic that in many instances were truly remarkable.[2,7–10]

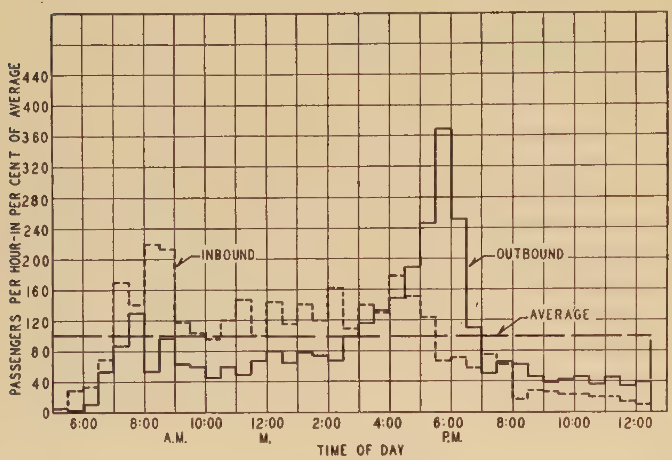


Figure 1. Typical curve of passengers per hour as a function of the time of day

Factors That Determine the Choice of Vehicle

The foregoing discussion indicates that many factors influence the choice of vehicle in a given case. These may be classified roughly into two groups; first, those that have to do with the psychological appeal of the vehicle and, second, the economic factors.

The psychological or human elements of the problem are quite difficult or impossible to determine quantitatively and their relative importance in a given case is largely a matter of opinion or personal preference. For this reason no attempt has been made to determine which vehicle will have the greatest popular appeal but rather attention has been confined to the purely economic elements involved. Therefore, in what follows it is assumed that for equal headways the different vehicles are all equally capable of attracting patrons.

Economic Considerations

In determining the best vehicle with which to modernize a given line, three factors are of primary importance. These are, first, the net return; that is, the excess of income over total operating expenses; second, the possible headways; and third, the investment required.

The first is important because it determines the most economical vehicle to use. The second is important because it fixes the frequency of service and therefore, from the patron's viewpoint, largely the quality of the service rendered. The third is important because it determines the amount of new capital that must be provided.

For each kind and size of vehicle the net return, the headway, and the required investment all vary with the traffic to be handled. In a given case, the vehicle selected will normally be the one that can be operated most economically for the traffic existing. There are, however, exceptions to this rule. Sometimes, particularly with lines of light traffic, the most economical vehicle would require headways too large to give reasonably good service. In that case a smaller vehicle, operated with shorter headways, is desirable even at some sacrifice in the net return. Other exceptions may be found. For instance, the need to limit the number of types and sizes of vehicles on the system may result in choice of a vehicle other than the one that will give the best economy.

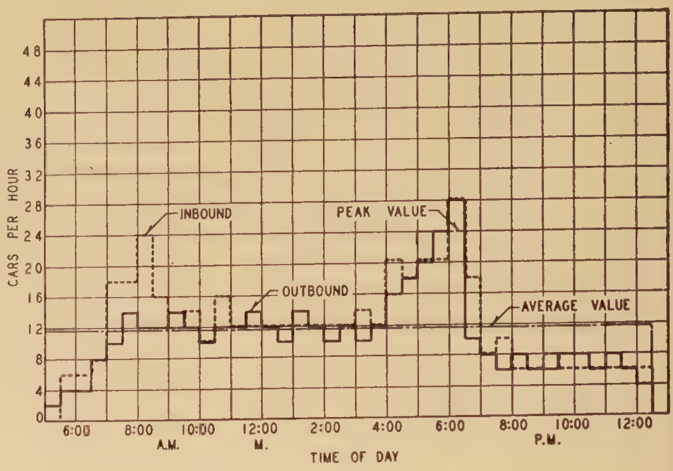


Figure 2. Typical daily car-demand curves

The reader has probably surmised that the problem of selecting the proper vehicle involves individual study of each line. This is the case particularly if an accurate forecast of the probable net return with the new equipment is to be obtained. However, as was noted previously, each vehicle has a certain volume range of traffic over which it is most economical. If this is known beforehand, then the problem of selection is greatly simplified.

Basic Data. Before the most economical traffic density range is determined for each type of vehicle the basic data must be established on which the solution of the problem depends.

The following general data were assumed to apply to all vehicles alike (the basis for each assumption is discussed in greater detail below): average schedule speed, 13 miles per hour; interest rate, five per cent; average fare, six cents; and duration of service, $19^1/_2$ hours per day. Additional data applicable to specific vehicles are given in table I.

These data were derived from various sources. The average schedule speed of 13 miles per hour was estimated. As was mentioned before, the PCC car is designed to have a schedule speed of 14 miles per hour, with eight seven-second stops per

mile. The trackless trolley is equally fast and modern busses could probably do as well in any service in which they would likely be used.

This value is probably high for dense traffic but it should approximate average conditions fairly closely. Admittedly, schedule speeds vary on different lines, but in general on a given line the schedule speed will be very nearly the same regardless of vehicle type.

The interest rate is taken at five per cent, as being approximately average. A low rate would be more favorable to those vehicles that require large capital investments.

The average fare of six cents is probably too low for the country as a whole. Its value would not affect the region of best economy in any case, although it would have a very decided effect on the net return. Consequently the comparison, as between vehicles, is the same regardless of the fare. The value of six cents was assumed because it is almost exactly the average fare, including transfers, etc., for the Seattle Municipal Railway System.

An allowance of ten per cent of the vehicles required on the peak was made for spares. This favors the gas busses slightly for, generallyspeaking, the availability of the electric vehicles is better than that of gas units.

The data listed in table I were also drawn from several sources. The values for vehicle-unit costs (column 2 of table I) were taken in part from manufacturers' bid prices, in part from published prices, or were estimated in those cases where information was not available from either. To determine accurate unit-cost data for the gas busses is particularly difficult because of the wide variations in specifications and manufacture for busses nominally of the same passenger capacity.

Depreciation. The life of new street cars is taken as 20 years; that of the trackless trolley as 10 years. These assumptions are close to the usual practice with regard to these vehicles. Except where stated otherwise, the useful life for the 30- and 40-passenger gas busses is taken as $6^2/_3$ years. For the 22-passenger gas bus, because of its generally cheaper construction, a useful life of 3 years is assumed. Practice with regard to depreciating gas busses varies considerably with different operating companies, the useful life assumed generally varying between 5 and 10 years.

As a matter of fact, any of these vehicles can be maintained almost indefinitely. Some street cars, still in operation, are more than 35 years old; similarly, trackless trolleys will last more than 10 years, and gas busses more than $6^2/_3$ years. In fact, the average age of the gas busses now in use in this country is estimated to be over 10 years. But few people nowadays want to keep a street car 35 years. Neither will they want to keep a trackless trolley or a gas bus more than a reasonable length of time. From a practical standpoint, if a vehicle is kept in service too long, operating costs go up, and generally patronage goes down. Modern advertising has taught the public to expect new models in its transit vehicles as well as in its private automobiles.

The assumed life of $6^2/_3$ years is undoubtedly very conservative for busses of good manufacture. Of course, if the depreciation rate were reduced these vehicles would make a somewhat better showing. Similarly, if the depreciation rate for the street cars were increased it would suffer by comparison. The effect of changing the depreciation rate is shown more in detail, for the case of the 22-passenger gas bus, in figures 20 and 21.

Use of a vehicle having a shorter life is not without advantage. For example, suppose that the condition of traffic and track on a given street-car line were such that the line could be modernized at practically equal cost with either new street cars or gas busses. Equal cost means that if new street cars are used they must be kept in service for 20 years in order to recover the investment. If on the other hand, the line be modernized by using, say, 40-passenger gas busses, which are "written off" the books in $6^2/_3$ years, the line could have new equipment of the same or better type, should better-type equipment be then available, every $6^2/_3$ years. Or if at the end of the depreciation period the equipment had some useful life remaining it could be kept in service until completely worn out. Each time new equipment is put into service the result will normally be an increase in traffic, for which the type of vehicle should have credit.

Another disadvantage of a long-term program is that frequently community development makes necessary improvements, such as grade changes, repairing operations, etc., which were not taken into account in the original calculations.

The depreciation rate on the new investment in track, which is assumed also to include any necessary rehabilitation of the overhead, has been taken at four per cent. The assumption is that street-car operation will be continued indefinitely. If street-car operation is to be discontinued at the end of the usual life (20 years) of the new rolling stock, the depreciation rate on the new investment in track will properly be five instead of four per cent. The depreciation rate on the overhead for the trackless trolley has been assumed to be five per cent. The above procedure is more than fair to the street car.

No attempt has been made to depreciate the old investment in track or overhead on the ground that if present street cars are to be replaced, for example by gas busses, all the present investment in track will have to be retired. Salvage value is ignored in all cases. Also no allowance is made for removing the old rails from the street in case rail operation is abandoned. Probably the most satisfactory method of handling this problem is to cover the old rails with asphalt until repaving becomes necessary, at which time they can be removed inexpensively.

Operating Costs. The operating costs per vehicle mile given in table I are estimates. Some of the values check reasonably well with recently published data[11] for similar vehicles. In different

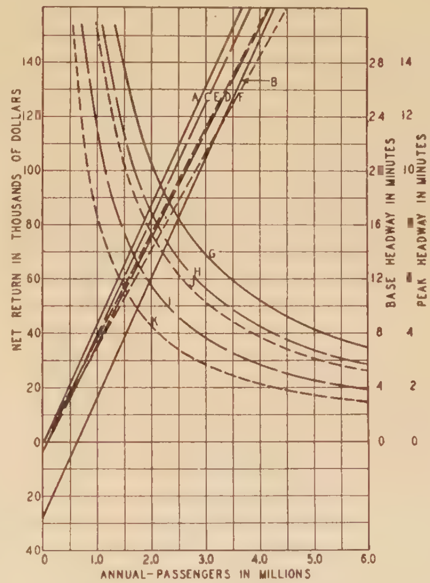


Figure 3. Net return and headway versus annual passengers; three-mile line, L=0.9, m=2

A—Net return, PCC car, with no track rehabilitation cost
B—Net return, PCC car, with track at $100,000 per double-track mile
C—Net return, 44-passenger trackless trolley
D—Net return, 30-passenger trackless trolley
E—Net return, 40-passenger gas bus
F—Net return, 22-passenger gas bus
G—Headway, PCC car
H—Headway, 44-passenger trackless trolley
I—Headway, 30-passenger trackless trolley
J—Headway, 40-passenger gas bus
K—Headway, 22-passenger gas bus

parts of the country operating costs vary considerably, owing primarily to differences in wages, and in fuel and power costs. The values quoted are as nearly average as could be determined from the data available. In sections where electric energy is expensive, the operating costs for the electric vehicles will be more than the figures quoted in table I, while cheap gasoline will tend to lower those for the gas busses.

Another cost, difficult to determine in a general study of this kind, is taxes. The difficulty arises from the fact that there are almost as many and varied methods of assessing taxes against transit systems as there are transit systems. In a specific case the taxes will be known and can be taken into account. The fact that taxes are herein neglected will not, in general, greatly alter the region of best economy for the various vehicles, because taxes would affect all to almost the same degree.

Determination of the Most Economical Traffic-Volume Range for Each Vehicle. From the basic data, previously established, values of annual-passengers, annual-vehicle miles, annual-revenue, annual-operating cost (exclusive of interest and depreciation), required investment, interest, and depreciation, total operating cost, and net return, were computed for various assumed values of headway and length of line for each of the vehicles shown in table I. These values were so chosen as to cover the usual range to be met with in practice.

The quantities enumerated above may

Table I

Type of Vehicle	Unit Cost of Vehicle (Dollars)	Vehicle Seating Capacity	Depreciation (Per Cent) Vehicles	Track	Overhead	*Average Operating Cost (Cents Per Mile)
54-passenger PCC car	15,000	54	5	4	4	23.0
44-passenger trackless trolley	13,000	44	10	None	5	18.5
30-passenger trackless trolley	9,500	30	10	None	5	15.5
40-passenger gas bus	10,000	40	15	None	None	21.0
22-passenger gas bus	2,200	22	33$^1/_3$	None	None	14.25

* Excluding interest and depreciation.

be calculated individually; or, more conveniently, particularly if only the net return is required, the various relationships can be put into a single equation, thus:

$$R = AF - 365k_1lt_0C_a - \frac{k_2PUlC_p}{V} - \frac{k_4lT}{2} \qquad (1)$$

or

$$R = \frac{alF}{2} - 365k_1lt_0C_a - \frac{k_2PUlC_p}{V} - \frac{k_4lT}{2} \qquad (2)$$

or again

$$R = 730LFSt_0C_a - 365k_1lt_0C_a - \frac{k_2PUlmC_a}{V} - \frac{k_4lT}{2} \qquad (3)$$

where

R = net return
P = 1.1 = ratio of total vehicles, including spares to the vehicle required on the peak
F = average fare in dollars = 0.06
t_0 = hours of service per day = 19.5
V = schedule speed = 13 miles per hour
U = unit cost of vehicle in dollars
k_1 = average operating cost per vehicle-mile in dollars, exclusive of interest and depreciation
k_2 = interest rate plus depreciation rate (in decimal) on vehicles
k_4 = interest rate plus depreciation rate (in decimal) on track and overhead (street car) or on overhead (trackless trolley)
h = headway in minutes
C_p = cars per hour during peak period
C_a = average cars per hour = average ordinate of car-demand curve
T = cost of rehabilitating track and overhead, for the street car, or cost of overhead for the trackless trolley, in dollars per double track mile (DTM)
S = seating capacity of vehicle
L = average loading of vehicle, that is, the ratio of the average number of passengers per trip to the vehicle seating capacity, in decimals
l = round-trip length of line in miles
A = total annual passengers
a = total annual passengers per route mile $= 2A/l$
m = ratio (in decimal) of the cars per hour on the peak (C_p) to the average, or base, cars per hour (C_a); is also equal to the ratio of the average, or base, headway to the peak headway

The first term, AF, is the annual gross income; the second term, $365k_1lt_0C_a$, is the yearly operating cost exclusive of

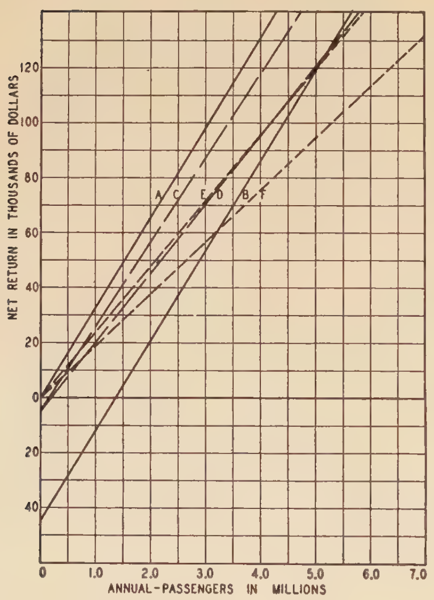


Figure 4. Net return versus annual passengers, five-mile line, L = 0.9, m = 2

Curve designations same as in figure 3

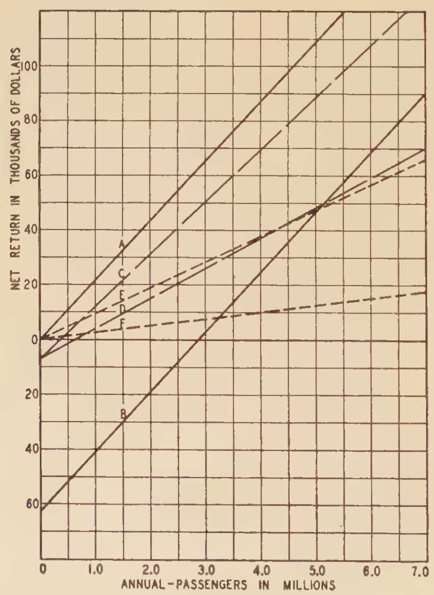


Figure 5. Net return versus annual passengers, seven-mile line, L = 0.9, m = 2

Curve designations same as in figure 3

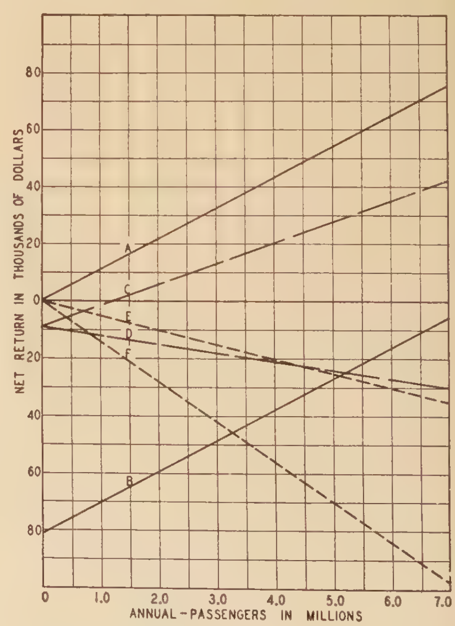


Figure 6. Net return versus annual passengers, nine-mile line, L = 0.9, m = 2

Curve designations same as in figure 3

interest and depreciation; the third term, k_2PUlC_p/V, is the interest and depreciation on the vehicles alone; while the last term $k_4lT/2$, is the interest and depreciation on the new investment in track and overhead, if the street car is under consideration, or the overhead in case of the trackless trolley.

Equation 1 assumes the same schedule every day, including Sundays and holidays. The error introduced only slightly alters the region of best economy for it affects all vehicles to much the same degree. This error could be eliminated by computing separately the annual vehicle-miles for weekdays and for Sundays and holidays, then adding. The additional accuracy obtained would hardly be worth while for the present purpose.

Figure 1 shows typical curves of passengers per hour as a function of the time of day for an existing street-car line. Figure 2 shows the corresponding curves of cars per hour with a 44-passenger vehicle, plotted to the same abscissas. The curves of both figures 1 and 2 were plotted from data taken during a traffic count on this line. For each size of vehicle there are vehicle-demand curves corresponding to those of figure 2.

The connection between the curves of figures 1 and 2, and equations 1, 2, and 3, may be shown as follows: the second term of equation 1 shows that the operating cost is proportional to the quantity t_0C_a, the area under the car-demand curve of figure 2. The daily vehicle-miles, and consequently the operating cost also, are dependent on the length of the line and on the area under the car-demand curve, not upon the shape of this curve, unless of course changing the shape of the curve will alter the average cost of operation per vehicle-mile. The third term of equation 1 contains the term C_p. This is the peak value, averaged over the time of a round trip, of the car-demand curve.

The total number of daily passengers is the area under the passenger-time curve. The total of annual passengers (A) must equal that of passengers per vehicle-mile multiplied by the annual vehicle-miles, or

$$A = \frac{\text{(average vehicle-loading)(seating capacity)(annual-vehicle-miles)}}{\text{(route-miles of line, one way)}}$$

hence

$$A = \frac{2LS}{l}(365lt_0C_a) = 730LSt_0C_a \qquad (4)$$

Equation 4 shows that for a given vehicle size and loading the annual-passenger total is also proportional to the area under the car-demand curve which is t_0C_a. If the relationship of equation 4 and also that of $C_p = mC_a$ is substituted into equation 1, equation 3 is obtained.

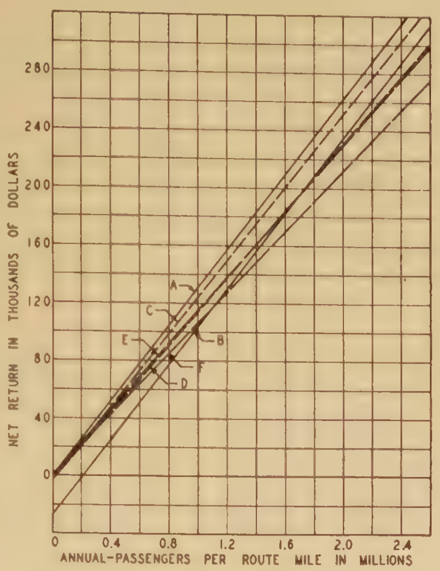


Figure 7. Net return versus passenger density, three-mile line, L = 0.9, m = 2

Curve designations same as in figure 3

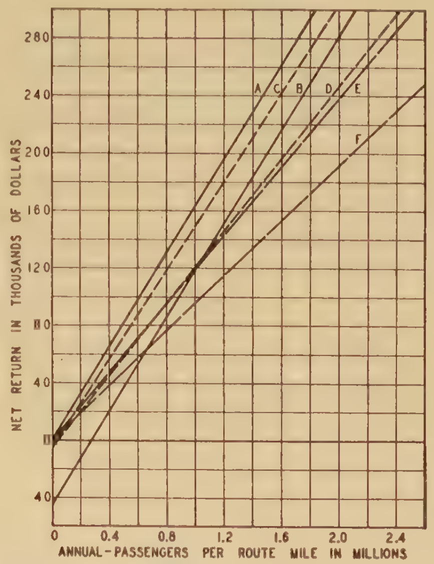


Figure 8. Net return versus passenger density, five-mile line, L = 0.9, m = 2

Curve designations same as in figure 3

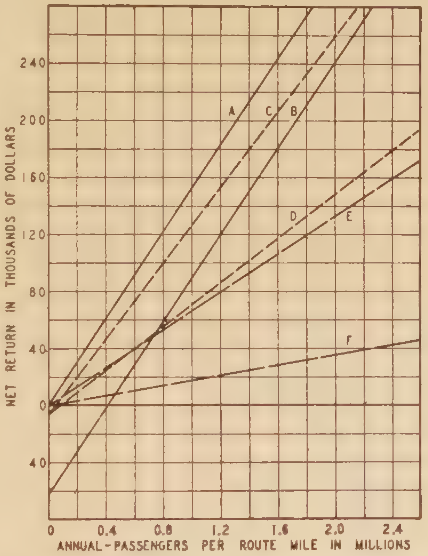


Figure 9. Net return versus passenger density, seven-mile line, L = 0.9, m = 2

Curve designations same as in figure 3

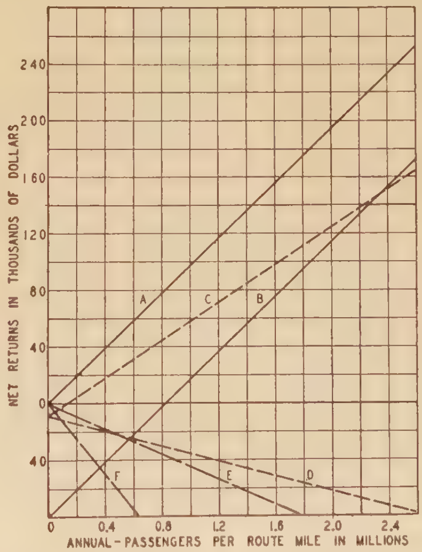


Figure 10. Net return versus passenger density, nine-mile line, L = 0.9, m = 2

Curve designations same as in figure 3

Results. The results of applying the above method of analysis are shown graphically in the following curves.

Figures 3 to 6 inclusive, show the relationship between net return and annual passengers for lines of varying length, assuming a constant average loading of 0.9 and a ratio of average to peak headway of two. In figure 3 are shown, in addition, curves of base and peak headway as a function of annual passengers for the different vehicles. Since the headway, for a given size of vehicle and number of annual passengers is independent of the length of line, headway curves are not shown in figures 4, 5, and 6, for they would be identical with those of figure 3.

Inspection of figures 3 to 6 inclusive reveals a number of interesting facts. For example, the curves show that, if the present track is in such good condition that it will require no more than normal

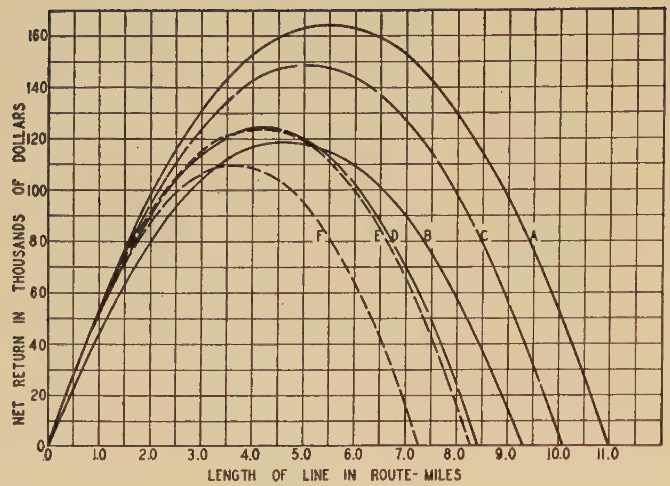


Figure 11. Net return as a function of length of line at constant traffic density; $a=10^6$, $L=0.9$, $m=2$

Curve designations same as in figure 3

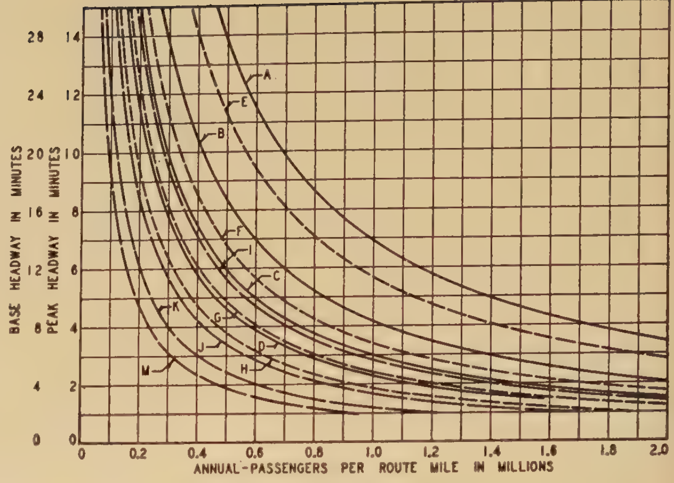


Figure 12. Headway as a function of traffic density

PCC car:
A—three-mile line *C*—seven-mile line
B—five-mile line *D*—nine-mile line

44-passenger trackless trolley:
E—three-mile line *G*—seven-mile line
F—five-mile line *H*—nine-mile line

22-passenger gas bus:
I—three-mile line *K*—seven-mile line
J—five-mile line *M*—nine-mile line

upkeep during the life (20 years) of the new rolling stock, it will be more economical to modernize with new street cars than with any other vehicle. If, on the other hand, the track must be rebuilt at a cost of $65,000[13] per double-track mile, which is about the minimum cost at which track in paved streets can be rebuilt, the 44-passenger trackless trolley is more economical than the street car, up to a value of annual passengers well beyond the range of the curves. This point will be discussed more in detail later.

The curves also show that, for values of annual passengers below approximately 2,000,000 passengers per year, the headways with any of the three larger vehicles will be very poor indeed, unless these vehicles are operated at a smaller average load than 90 per cent, which would in turn reduce the net return. When the annual load falls to 1,000,000 passengers or less, the small (22-passenger) bus is the only vehicle that can be run with a reasonably good headway. This point will also be discussed more completely presently.

Comparison of figure 3 with figure 5 shows that the net return, for a given number of annual passengers, is greater for the three-mile than for the seven-mile line. This result is to be expected, since for the same number of annual passengers, other factors remaining the same, the passengers per vehicle-mile must be larger on the three-mile than on the seven-mile line. But in order to have the same number of annual passengers, the annual-passengers per route-mile must be greater on the short line. This relationship in turn requires that the population density, assuming equal riding per unit of population, must be greater on the short line. A more interesting comparison is obtained, as between lines of different lengths, if the annual-passengers per route-mile, instead of annual passengers, is made the independent variable.

Accordingly in figures 7 to 10 inclusive, are shown curves of net return as a function of annual-passengers per route-mile. The vehicles used, and the other pertinent data, are the same as for figures 3 to 6 inclusive. As will be noted, while the latter curves have essentially the same shape as the former, the relative values have considerably changed. The net return for a given passenger density is greater for lines of intermediate length than for either very long or very short ones. This result immediately leads one to suppose that for a given traffic density there is a definite length of line that will give a maximum net return. Inspection of equation 2 and of the curves of figure 11 confirms this supposition.

In figure 11 are shown curves of net return versus length of line, for the same vehicles as before, for a constant traffic density of 1,000,000 passengers per route-mile per year. For each vehicle there is one definite length of line that will yield the greatest return. This optimum length is greater, the lower the total cost of operation per passenger mile. The curves also show that each vehicle has a maximum length of line beyond which a deficit will appear. This finding agrees with operating experience that long lines are relatively unprofitable unless local traffic is sufficient to keep the passengers per vehicle mile at a profitable level.

In figure 12 are shown curves of headway versus traffic density for 54-, 44-,

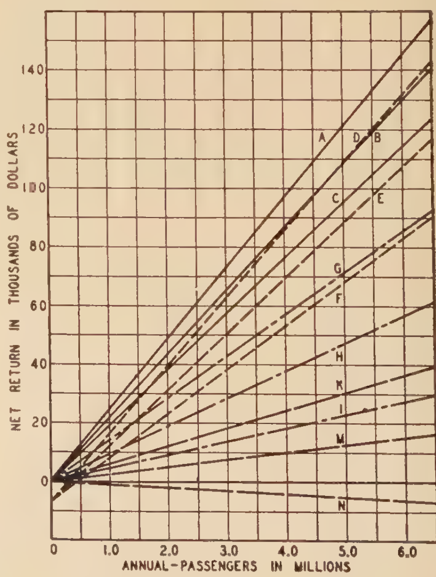


Figure 13. Curves of net return versus annual passengers for different values of the ratio m; seven-mile line, L=0.9

PCC car:
A—$m=1$ *B*—$m=2$ *C*—$m=3$

44-passenger trackless trolley:
D—$m=1$ *E*—$m=2$ *F*—$m=3$

40-passenger gas bus:
G—$m=1$ *H*—$m=2$ *I*—$m=3$

22-passenger gas bus:
K—$m=1$ *M*—$m=2$ *N*—$m=3$

and 22-passenger vehicles, for three-, five-, six-, and nine-mile lines. These curves show that for a given number of passengers per route mile and size of vehicle, the longer the line the better the headways will be. This finding agrees with operating experience. As is common knowledge, it is difficult to give close headways on short lines with any but small vehicles, while on long lines it is relatively easy to provide good headways even with large units.

Effect on Net Return of Changes in Ratio of Peak to Average Number of Vehicles per Hour. In figures 3 to 11 inclusive, the ratio (m) of peak to base cars per hour was assumed to be two, which is almost the exact value for the line of figures 1 and 2. The value of m is a measure of the peak service necessary in terms of the average, and therefore of the required investment in vehicles. For this reason the net return will depend, to a considerable degree, upon the magnitude of m. This will be particularly the case with equipments that have a high first cost or a high depreciation rate.

On light lines where, for the sake of maintaining certain minimum standards of service, considerably better headways are usually provided during the off-peak period than the traffic warrants, the value of m may be less than two. On the other hand, on certain routes serving highly

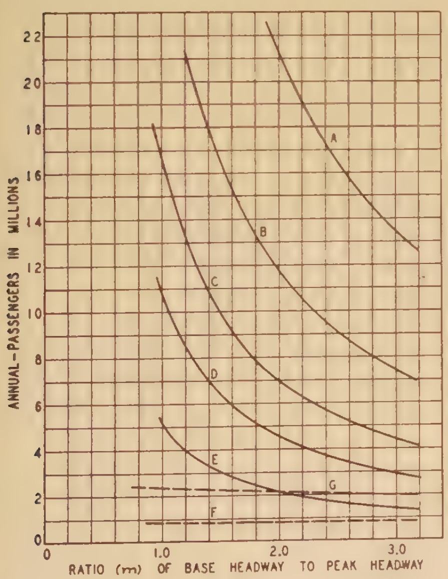


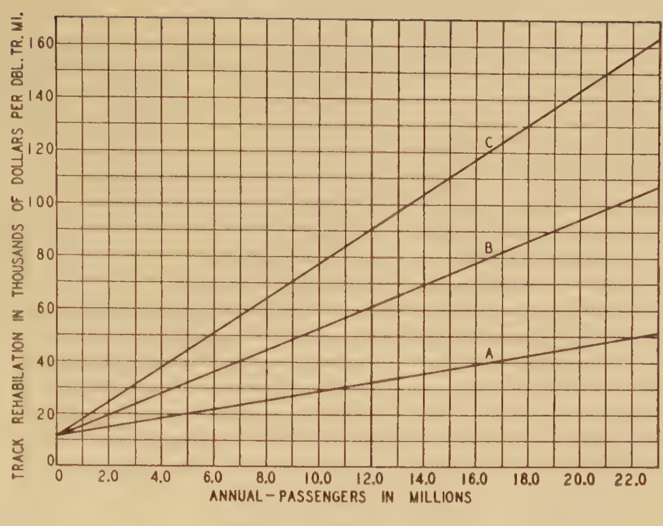
Figure 14. Annual passengers as a function of m for equal net return; L = 0.9

PCC car versus 44-passenger trackless trolley; track per double-track mile at:
A—\$100,000 B—\$60,000 C—\$40,000
D—\$30,000 E—\$20,000

44-passenger trackless trolley versus 40-passenger gas bus:
F—Gas bus at 21 cents per mile
G—Gas bus at 20 cents per mile

Figure 15. Track rehabilitation cost versus annual passengers for equal net returns, PCC car and 44-passenger trackless trolley; L = 0.9

A—$m = 1$
B—$m = 2$
C—$m = 3$



industrialized centers the value may be greater than three.

Figure 13 shows the variation in net return with annual passengers for different values of m, so chosen as to cover the range likely to be met with in practice. This figure also shows that the region of best economy for each vehicle also varies with the value of m. As predicted above, the advantage is in favor of the vehicles of low cost and low depreciation rate.

In order to show the region of best economy for the PCC car, the 44-passenger trackless trolley, and the 40-passenger gas bus, the curves of figure 14 were computed. Any individual curve is the boundary line between the regions of maximum economy, under the stated conditions, for the two vehicles to which it refers. To make this point more clear suppose, for example, that a new investment of \$40,000 per double-track mile will be needed to rehabilitate the track on a certain existing street-car line that is to be modernized. If the point corresponding to the annual traffic and the value of m for this line is located above and to the right of curve *C* of figure 14, the street car will give the more economical service; but if the point falls below and to the left of curve *C* the trackless trolley will give a larger net return. This conclusion does not give the trackless trolley credit for the fact that, because the headways with it will be approximately 22 per cent better than with the street car, it will therefore tend to attract a greater traffic increase.

To illustrate further the use of the curves of figure 14, the line of figure 2 is assumed, for which m is slightly greater than two. This line has an annual traffic of approximately 6,500,000 passengers. Curve *C* shows that, if a new investment of less than \$40,000 per double-track mile is required to rehabilitate the track on this line, the street car will be the more economical; but if the new investment in track must exceed \$40,000 per double-track mile, the 44-passenger trackless trolley will give service that is more economical and at the same time more frequent, by approximately 22 per cent.

Figure 15 shows the amount that may be spent in rehabilitating the street-car tracks for equal return with the 44-passenger trackless trolley for different values of m. For example, assume a line that has an annual traffic of 8,000,000 passengers and a value of m equal to three. Curve *C* of figure 15 shows that if track rehabilitation required an expenditure of less than approximately \$64,000 per double-track mile, the street car would be the more economical, but that if the expenditure required exceeded that amount the trackless trolley would be the more economical as well as giving more frequent service.

Importance of Average Loading. In figures 3 to 15 inclusive, the average passengers per vehicle was maintained constant at 0.9 or 90 per cent of the vehicle-seating capacity. Equation 3 shows that a small change in the value of L, the average vehicle loading, will produce a relatively large effect on the net return. This relationship is shown by the curves of figures 16 and 17. The curves show that, for the three-mile line, a 20-per-cent decrease in the value of L (which is another way of saying a 20-per-cent decrease in passengers per vehicle-mile) produces a decrease in the net return that varies from approximately 26 per cent, for the street cars, to about 32 per cent for the 22-passenger bus; while for the seven-mile line the same percentage of decrease in L produces a decrease in the net return that varies between approximately 41 per cent, for the street car, and about 147 per cent for the 22-passenger gas bus. This shows the great importance—one might almost say the

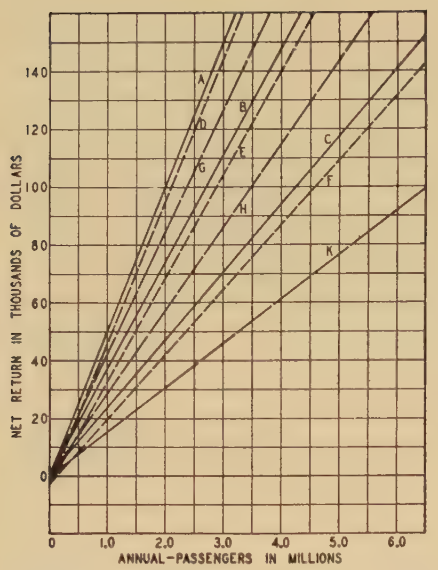


Figure 16. Net return as a function of annual passengers at constant values of vehicle loading; three-mile line, m = 2

PCC car, no track rehabilitation:
A—L = 1.0 B—L = 0.8 C—L = 0.6
44-passenger trackless trolley:
D—L = 1.0 E—L = 0.8 F—L = 0.6
22-passenger gas bus:
G—L = 1.0 H—L = 0.8 K—L = 0.6

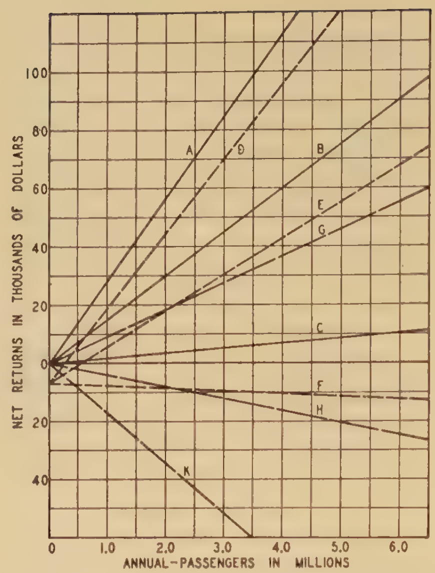


Figure 17. Net return as a function of annual passengers at constant values of vehicle loading; seven-mile line, m = 2

PCC car, no track rehabilitation:
A—L = 1.0 B—L = 0.8 C—L = 0.6
44-passenger trackless trolley:
D—L = 1.0 E—L = 0.8 F—L = 0.6
22-passenger gas bus:
G—L = 1.0 H—L = 0.8 K—L = 0.6

necessity—of keeping the average loading high, particularly on long lines with vehicles that have relatively high operating costs per passenger mile.

This more than proportional change in net return with a given change in loading, is one factor that makes possible, in certain cases—principally with light lines—replacement of a larger vehicle with one of less capacity, thus giving a more attractive headway, and still operating at a profit. During periods of light load, with the same or better headway, the small vehicle will be more nearly loaded, thus raising the value of the average passengers-per-vehicle-mile.

The factors involved can perhaps be most conveniently illustrated by use of an actual example. Figure 18 shows the relationship between passengers-per-hour and the time of day for an existing 6.9-mile street-car line having an annual traffic of approximately 1,745,000 passengers. It is proposed to modernize this line, using the vehicle that will give the best all-around performance. Figure 5 indicates that this line can probably be operated most economically with a 44-passenger trackless trolley, unless the track is in such good condition that an investment of approximately $25,000 per double-track mile will restore it to normal; in this case the PCC car would be the most economical. But reference to the headway curves of figure 3, which also apply to figure 5, indicates that the possible headways, with either the 44-passenger trackless trolley or the PCC car, will not be particularly good, certainly not good enough to attract any considerable amount of additional patronage. This result immediately suggests the desirability of using a smaller vehicle if such a course can be justified economically.

Figure 19 shows vehicle-demand curves for units of the several sizes made up from the traffic curves of figure 18. For the most part the curves of figure 19 provide very liberal schedules. In no case would passengers have to stand during the mid-day period. This insurance is highly desirable if increased riding is to be encouraged, particularly during the off-peak period. Also the maximum headway was set at 20 minutes, excepting only after 11:00 p.m. After 11 the headway is 30 minutes. The same schedule was assumed for both directions of travel.

Because of the large difference in traffic in the two directions on this line it is difficult to keep the average vehicle loading at a good figure without at the same time forcing some passengers to stand, in the heavy direction of travel, even during the off-peak period. The operating results to be expected for the various conditions and vehicle sizes are set out in table II. Line 1 of table II shows the forecast for the PCC car, assuming an average track rehabilitation cost of $20,000 per double-track mile. If the required expenditure for track rehabilitation is greater than approximately $24,500 per double-track mile, the street car will incur a deficit.

Line 2 of table II shows the projected results for the 44-passenger trackless trolley, with present traffic and a vehicle-demand as shown by curve *C* of figure 19. By decreasing the headways after 7:00 p.m. to values more nearly in line with the traffic after that time, and one or two other minor adjustments in schedule, the $899 deficit may be converted into a net gain of $6,556.

Line 4 shows the results to be expected if the new equipment is able to attract a ten-per-cent increase in traffic. This item shows very strikingly the improved results with even a very moderate gain in patronage. Items 5, 6, and 7 are the same as items 2, 3, and 4, except that they apply to the 40-passenger gas bus. Curve *C* is liberal enough so that a ten-per-cent, and better, increase in traffic can be accommodated without an increase in facilities.

Items 8 and 9 are for the 30-passenger trackless trolley. The first is for present traffic; the second assumes an increase in traffic of 15 per cent (15 per cent is assumed because of the better headways offered by the smaller vehicle). With the 15-per-cent increase in patronage it would be desirable to augment the facilities, as shown by curve *B*. The net return, with the 30-passenger trackless trolley and the 15-per-cent increase in traffic, is $10,502 as compared with $9,571 for the 44-passenger trackless trolley with a 10-per-cent increase in traffic. In addition, the headways with the smaller vehicle are much better and also, owing to fewer stops with it, its schedule speed would be higher.

A 30-passenger gas bus that cost $8,000 per unit and had a useful life of eight years (not $6^2/_3$ as assumed for the 40-passenger gas bus in figures 3 to 17 inclusive) would have to have an operating cost of not over 16.87 cents per mile, in order to equal the performance of the 30-passenger trackless trolley. Whether the gas bus could be operated for only 1.37 cents more per mile than the trackless trolley is doubtful. However, the gas bus would have a decided advantage, in that express service could be provided during the peak period without additional complication or expense; something not possible with the trackless trolley.

The small or 22-passenger gas bus, at 14.25 cents per vehicle-mile, shows a deficit on this line, unless the loading is kept

Table II

Item Number	Vehicle	Schedule Curve From Figure 19	Annual Passengers	Headway in Minutes: Peak	Headway in Minutes: Midday	Headway in Minutes: Evening Early	Headway in Minutes: Evening Late	Average Loading in Per Cent of Vehicle Seating Capacity	Passengers Per Vechicle Mile	Annual Miles Per Vehicle	Net Return in Dollars	Remarks
1	54-passenger PCC car	*D*	1,745,000	8.5	20	20	30	66.2	5.19	30,455	2,769	Track at $20,000 per double-track mile
2	44-passenger trackless trolley	*C*	1,745,000	6	15	20	30	68.6	4.37	26,297	*899	*Deficit
3	44-passenger trackless trolley	Not shown	1,745,000	6	15	30	30	76.3	4.86	23,643	6,556	
4	44-passenger trackless trolley	*C*	1,919,500	6	15	20	30	75.4	4.81	26,297	9,571	10 per cent traffic increase over (2) above
5	40-passenger gas bus	*C*	1,745,000	6	15	20	30	75.3	4.37	26,297	*2,228	*Deficit
6	40-passenger gas bus	Not shown	1,745,000	6	15	30	30	83.8	4.86	23,642	6,234	
7	40-passenger gas bus	*C*	1,919,500	6	15	20	30	83.0	4.81	26,297	8,242	
8	30-passenger trackless trolley	*A*	1,745,000	5	12	20	30	81.9	3.56	27,305	3,248	
9	30-passenger trackless trolley	*B*	2,006,750	4.6	10	20	30	86.5	3.75	27,701	10,500	15 per cent traffic increase over (2) above
10	30-passenger gas bus	*B*	2,006,750	4.6	10	20	30	86.5	3.75	27,701	4,472	15 per cent traffic increase. 30-passenger gas bus at $8,000 each. Eight-year life. Operating cost at 18 cents per bus mile

high. To accomplish this, passengers must stand in the heavy direction of travel, even during part of the midday period. This is very undesirable if off-peak riding is to be encouraged. The traffic on this line is too large for the most economical operation of the 22-passenger unit.

Undoubtedly the 30-passenger trackless trolley is the proper vehicle to use on this line, unless the cost figures for the 30-passenger gas bus are more favorable than is indicated above.

The above analysis shows very clearly the comparatively large gains in net return due to even small increases in patronage. Therein lies one of the opportunities of modernization. Experience has shown that where service is improved, increased riding results. The best way to improve service, particularly on light lines, is to decrease the headways by substituting smaller, faster, more economical units, operated on closer schedules. In many cases where this has been tried, the results[3] obtained have been remarkable. Lines that were otherwise unprofitable have been converted into money-makers. This is the field for the small bus, and accounts in part for its growing popularity.

The above analysis also shows the importance of adjusting schedules so as to keep the vehicle loading as high as possible, consistent with good service. It shows too what is meant by "operating the smallest vehicle possible within the economic limitations".

Operating Cost. As was mentioned previously, the operating cost, exclusive of interest and depreciation, is the most important of the items of expense in the operation of a transit line. Its importance is indicated by the curves of figures 20 and 21. These show, first of all, that on a short line the operating cost is relatively unimportant. For example, figure 20 shows that for the three-mile line, if the operating cost of the 22-passenger gas bus is reduced from 14.25 to 11 cents per mile, a change of approximately 23 per cent, the corresponding variation in the net return will be slightly less than 13 per cent.

For a long line the conditions are very different. Even small changes in operating cost produce relatively large variations in the net return. This is particularly true of the small units. These statements can be verified by reference to figure 21, which shows that, for a seven-mile line, if the operating cost of the 22-passenger bus varies over the same range of 23 per cent as assumed above, the corresponding change in the net return will be about 72 per cent instead of 13.

In the curves of figures 3 to 10 inclusive,

Figure 18. Passengers per hour as a function of the time of day

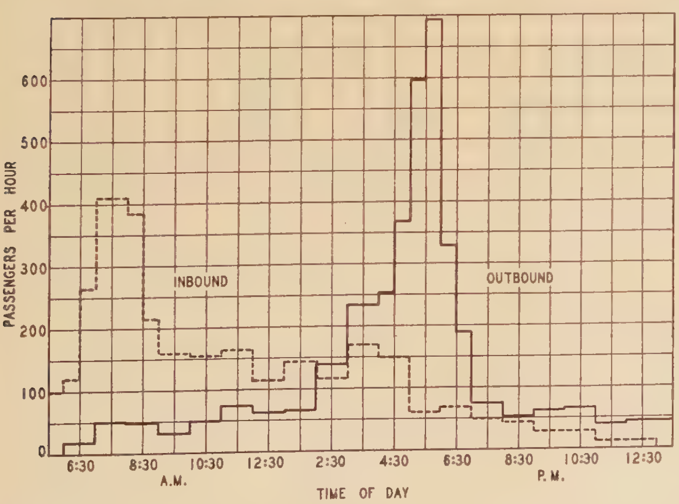
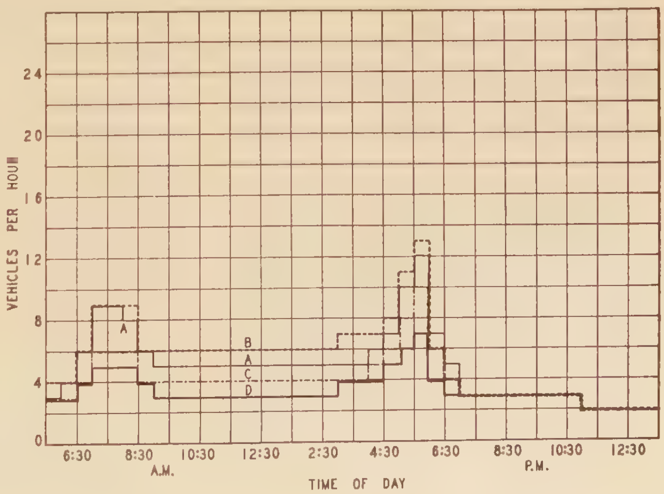


Figure 19. Car-demand curves

A—30-passenger vehicle, present traffic
B—30-passenger vehicle with 15 per cent traffic increase
C—40- or 44-passenger vehicles
D—54-passenger PCC car



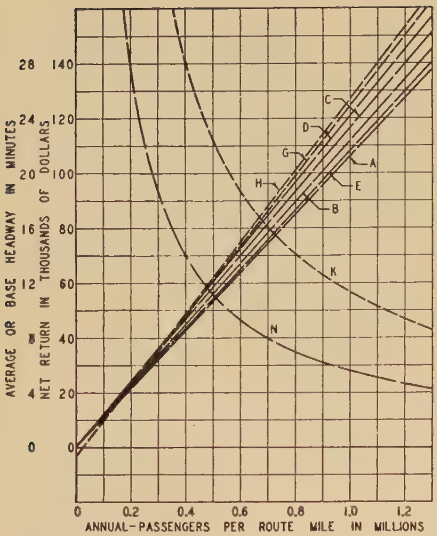


Figure 20. Net return versus passenger density for the small bus; three-mile line, L = 0.9, m = 2

22-passenger gas bus, three-year life; operating cost per mile at:
A—14¼ cents C—12 cents
B—13 cents D—11 cents

22-passenger gas bus, four-year life:
E—Operating cost 14¼ cents per mile

44-passenger trackless trolley, ten-year life; operating cost per mile at:
G—18½ cents H—17½ cents

K—Headway, 44-passenger trackless trolley
N—Headway, 22-passenger gas bus

the operating cost of the small bus is taken as 14.25 cents per bus mile. This value should be conservative for this unit; in fact some transit companies[12] have operated it for approximately 11.75 cents per mile, exclusive of taxes, interest, and depreciation.

The importance of a low operating cost is strikingly illustrated by the curves of figure 21. This figure shows that an increase in the normal life of this vehicle from three years to four years has about the same effect on the net income as a decrease in the operating cost of one-half cent per mile. Also, it shows that if the 22-passenger gas bus could be operated for ten cents per mile it would be more economical than the 44-passenger trackless trolley at 18.5 cents per mile, up to an annual load of approximately 5,000,000 passengers.

If this vehicle could be operated at such a low figure its usefulness would be very greatly increased. For instance, service would be possible on lines of much lighter traffic than is now economical. Of course, a decrease in operating expense is equally important with any of the other vehicles. The small bus was used for illustration because the results with it are perhaps more striking.

The fact was mentioned previously that to keep equipment in service too long is unprofitable. The small bus is more likely to fall under this rule than any other vehicle. For the conditions shown in figures 20 and 21 the average annual mileage per vehicle amounts to approximately 42,000. On the basis of three years of life, the annual interest and depreciation per unit amounts, at $2,200 each, to $843. If at any time the difference in operating cost per mile between the old and a new bus amounts to as much as two cents per mile, the saving in operating cost will be enough to pay the interest and depreciation on a new vehicle.

A much more important consideration is that patronage falls off if the vehicle is kept in service too long. As was indicated previously, only a very small drop in patronage would be required to reduce the net return by an amount equal to the carrying charges on a new vehicle. Obviously it is unprofitable to keep old equipment in service too long, particularly since new equipment generally brings an increase in riding. With the more expensive equipments obsolescence and decreased riding would make the change desirable long before increased operating costs would have a very great effect.

Capital Costs. In figure 22 is shown for a representative case the amount of new investment required for varying values of traffic density. The curves show that the small bus requires by far the least investment of any of the vehicles considered. For the others the investment required, in vehicles alone, is not greatly different; but when the cost of the overhead for trackless trolley, and of the track and overhead for the street car, are added, the required investment, especially for the street car, may be greatly increased.

Conclusions

The first conclusion to be drawn from the previous discussion is that if the present track has a useful life remaining equal to that of new rolling stock, the PCC car is the most economical vehicle to use in modernizing an existing line; if in addition the volume of traffic is sufficient to warrant a reasonable frequency of service with so large a unit, the PCC car will also probably be the best vehicle to use.

If on the other hand track rehabilitation is necessary, then—the choice depending on the expenditure required for this work and on the traffic density—either the trackless trolley or the gas bus may be more economical as well as offering more frequent service.

Figure 14 shows that, if the track must be completely rebuilt at a cost of approximately $60,000 per double-track mile, the 44-passenger trackless trolley is more economical than the PCC car up to values of annual passengers of approximately 5,500,000, 7,000,000, and 11,000,000, corresponding to values of m of four, three, and two respectively.

Five and one-half million passengers per year is fairly heavy traffic. The heaviest line in Seattle has an annual load of approximately 6,500,000 passengers with a value of m equal to practically two. (The curves of figures 1 and 2 are for this line.)

In a given case the above conclusions may be modified by a full consideration of the psychological factors involved. The quantitative relations may also be altered if the various costs are appreciably different from the values used above.

The principal advantage of the street car is its ability to handle heavy traffic, with sharp peak loads. In this connection it should be mentioned that at about the time this study was nearing completion one of the vehicle manufacturers announced a new rubber-tired vehicle,[14,16] available either as a trackless trolley or as a Diesel-electric bus, of practically street-car capacity. As no cost data were available on this vehicle it is not included in this report. But if, as would be expected, first cost, operating cost, depreciation, etc., for this unit are in line with corresponding costs for the smaller trackless trolleys now in use, the curve for this vehicle could be expected to occupy a

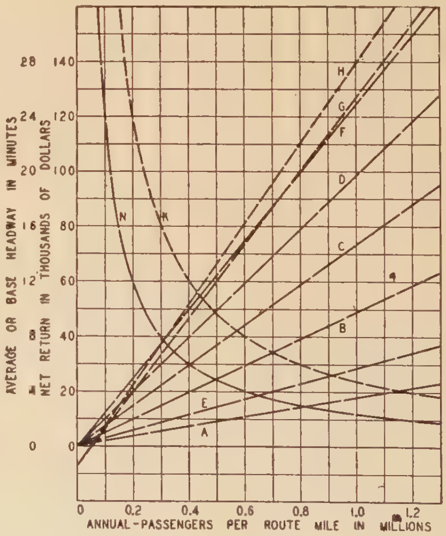


Figure 21. Net return versus passenger density for the small bus; seven-mile line, L = 0.9, m = 2

F—22-passenger gas bus, three year life operating cost per mile at ten cents

Other curve designations same as in figure 20

place, in figures 3 to 13 inclusive, very close to the curve for the PCC car without track-rehabilitation cost. If this should prove to be the case, and if the operating characteristics of the new vehicle are also satisfactory, the street car has a worthy competitor in the heavy-traffic field.

Unless some new development should bring much cheaper track, or a marked drop in interest rates occurs, it is probable that, as present tracks wear out, economic pressure will force the gradual retirement of the rail car from all except the very heaviest surface lines.

The future role of the trackless trolley and of the gas bus is not quite so clear, but for the near future the backbone of the transit system appears to be the trackless trolley, with gas busses on the lighter lines. Figure 14 shows that with an operating cost of $18^1/_2$ cents per mile for the 44-passenger trackless trolley and of 21 cents per bus mile for the 40-passenger gas bus, the trackless trolley is the more economical for all values of traffic greater than approximately 800,000 passengers per annum. If the operating cost of the gas bus can be reduced to 20 cents per mile the point of equal return is raised to approximately 2,000,000 passengers per year. Evidently the position of the line separating the regions of best economy for these two vehicles is very sensitive to small changes in the relative operating costs. The relative position of these two vehicles could be expected to vary considerably in different sections of the country due to differences in fuel and power costs.

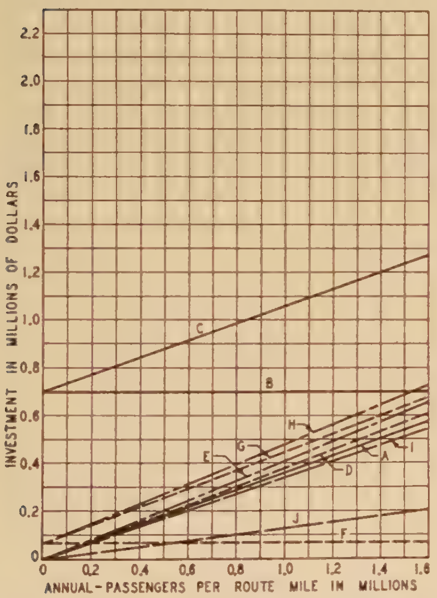


Figure 22. Investment required versus traffic density; seven-mile line, L = 0.9, m = 2

A—PCC car, vehicles only
B—PCC car, track only
C—PCC car, total
D—44-passenger trackless trolley, vehicles only
E—30-passenger trackless trolley, vehicles only
F—Trackless trolleys, overhead only
G—44-passenger trackless trolley, total
H—30-passenger trackless trolley, total
I—40-passenger gas bus
J—22-passenger gas bus

Undoubtedly the future will bring additional improvements in both vehicles that will reduce operating costs. The Diesel-electric is a step in this direction for the self-propelled vehicle. Whether the Diesel-electric, or perhaps the Diesel with hydraulic transmission, will be able to partially or completely supplant the electric vehicles remains to be seen. One influence that will tend to prevent this replacement is the fact that the trend in power rates is steadily downward while that of gasoline and oil prices is up.

The previous discussion also shows the importance of good engineering and good management in a prospective modernization program, not alone in selecting the most suitable vehicle for each line, but also in adjusting schedules and maintaining service so that riding will be encouraged.

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7. Why Pittsburgh Bought More PCC Cars, **W. J. Clardy.** *Transit Journal*, volume 81, number 6, June 1937, pages 184–6.

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13. Report of Way and Structure Committee, No. 13, *Proceedings*, American Transit Association, 1936, pages 942–83.

14. Biggest Yet, *Transit Journal*, volume 82, number 7, July 1938, pages 252–3.

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Discussion

G. M. Woods (nonmember; Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): Professor Hoard's paper is a valuable document to those engineers who are faced with a decision as to the type of vehicle to use for particular transit conditions. The study of the problem from the patron's standpoint as well as the economic standpoint is particularly desirable. The ability to attract new patronage and, by merit, to retain it must be the primary objective of any transportation system. Frequently economies in operation have been carried too far, with the result that gross revenues have decreased more rapidly than operating expenses. Fortunately, the modern vehicles and equipment available are not only more attractive to the passengers but they also are more economical to operate than the older vehicles.

Care must be exercised in a study of this type to avoid drawing general conclusions from a specific example. All of the conditions surrounding any particular application must be carefully analyzed and the correct basic data determined. The paper points out the material effect on the "regions of best economy" of relatively minor changes in operating cost.

Not only must present conditions be considered but thought must be given to the future also. For instance the author assumes a useful life of 20 years for street cars, 10 years for trolley coaches, $6^2/_3$ years for the larger motor busses, and 3 years for the 22-passenger busses. The price which must be paid for replacement vehicles at the end of 3, 6, or 10 years is unknown, although it is an important factor in long-term planning. As brought out in the paper the downward trend of power rates is in favor of electrically propelled vehicles.

L. C. Josephs, Jr. (Mack Manufacturing Corporation, Allentown, Pa.): Perhaps the most important factor in the choice of transportation equipment is the matter of merchandising and not engineering. There has perhaps been too much engineering in some places and not enough attention paid to the merchandising of transportation. The engineering side is apt to look on such factors as the cost of operation, without paying enough attention to the rather indefinite question of what makes people ride and how can more of them be made to ride.

In a general way, the engineering side of transportation equipment has to do more with the cost of operation, whereas the merchandising side of transportation has to do more with the question of gross income. Sometimes to get the optimum difference between income on one hand and operating expense on the other hand, it is necessary to do things that may seem wrong from a strictly engineering standpoint. That, however, is just what some of the railroads are doing on their modern streamlined trains,

where more attention is being paid to showmanship and less to operating economies. Maybe in this present day it is necessary to use considerable showmanship to get the people to ride on the urban transit systems.

H. E. McWethy (Twin City Rapid Transit Company, Minneapolis, Minn.): In discussing this paper I would first like to commend Professor Hoard on the thoroughness with which he has handled the technical aspects of a complicated problem. It is not easy to condense in so short a paper all of the diversified factors which should be and must be given consideration in the determination of the most economical type of vehicle to serve efficiently and safely the requirements of the riding population of any given community. While it is evident throughout the paper that Professor Hoard has had in mind the application of his general solution to the needs of the city of Seattle, Wash., it is also evident that the principles which he has set forth and the manner of solving the problem has a rather universal application to the street-railway systems of the United States. It is no disparagement to the excellence of this paper to say that many of the principles set forth therein have been used by the transportation industry in one form or another in the solution of similar problems for a considerable number of years. This is the first time, however, that we have had the advantage of having these methods set forth as a coordinated whole amply illustrated by the use of graphs.

I presume that our local engineers in the Twin City area would be happy if in this discussion I could take the graphs and formulas presented by Professor Hoard and apply them to the operations of the local transportation system of Minneapolis and St. Paul and thus determine just what should be done with this system. Obviously in a short discussion such an accomplishment is impossible. However, without attempting to reach definite conclusions, I would like to leave certain thoughts for your consideration which came to me as I went over this paper attempting roughly to evaluate our own performance in the light of the methods of analysis proposed in this paper.

At the outset Professor Hoard's analysis gives little if any consideration to the economy of the continuation of equipment which is at present in use on a given system. He assumes that all existing equipment has reached the point where it is uneconomical to continue its use further and that the choice of the transportation industry lies only with the PCC car, the trolley bus, and the gasoline bus. So far as our own system is concerned, we believe that this conclusion as to existing equipment being obsolete for the purpose of solving our transportation problems is not entirely warranted. We have reason to believe that the newer types of equipment must prove themselves by demonstrated economies over the equipment at present in use. In our case unless the newer types of equipment can demonstrate a much greater attractiveness to the public than the equipment at present in use, thus increasing the riding habit materially, there can be little question, so far as our entire system is concerned, as to the net economy of the continuance of the existing equipment in service. Quite rightly, we believe, Professor Hoard dismisses the question of increased riding which would follow the adoption of the new equipment as controversial and a matter of individual opinion, and he assumes for the purpose of his analysis that no change in the riding habit would follow the adoption of a different type of vehicle.

Having reached this conclusion, the remainder of the problem lies in the decision as to whether or not it is more economical with present patronage to continue in operation existing equipment than to adopt one or more of the three types of equipment which are suggested by Professor Hoard.

To justify the increased fixed charges on new equipment purchased there must be quite a marked differential in performance between the old and the new equipment. This differential may take the form of increased speed, greater comfort and convenience of passengers, or lower maintenance costs. The need for the new type of equipment will be most apparent on those properties where this differential between the old and new equipment is greatest. On properties where the differential is least no justification for a change may exist. We feel that the equipment on our property offers a case in point. Certain it is that good economics would frown on the adoption of stream lines without perceptible increase in the comfort and convenience of passengers, and it seems also fundamentally true that to destroy useful remaining life of well-maintained equipment without securing in the new equipment increased benefits of equal or greater value would be likewise unsound. We feel at the present time that the only case where the adoption of a new vehicle is warranted on this system is where a large section of track and paving on an existing line is worn out and must be replaced. In such a case the adoption of a rubber-tired vehicle may be more economical than the continuance of existing rail service.

When we come to compare operating data experienced on this system with that assumed by Professor Hoard, we find on the whole that a close similarity exists. For instance, in table I of his paper he shows 23 cents per car-mile as the average operating cost (excluding depreciation) for the PCC car. The comparable figure on our system for 1938 was 21.8 cents. For our busses which average 26 passengers each, the annual operating cost, exclusive of depreciation, was 15.78 cents per bus-mile, which may be compared with 21 cents per bus-mile which he has used for a 40-passenger gas bus and 14.25 cents for a 22-passenger gas bus.

The average fare per passenger (including transfer passengers) which Professor Hoard assumed of 6 cents compares with the average railway fare on this system of 5.52 cents. (Our record indicates that the average fare per *revenue passenger only* in Seattle approximates 8.3 cents as compared with 7.75 cents, the average fare on this system per revenue passenger.)

Now just a word as to the transportation property which serves the Twin City area. The population served approximates 800,000. The number of street cars is 715, operated on 459 miles of track. These cars operate approximately 21,860,000 car-miles annually and haul in the neighborhood of 100,000,000 passengers annually. This railway operation is supplemented by the operation of 116 gasoline busses which operate approximately 3,800,000 miles annually and carry approximately 4,500,000 revenue passengers. Of the 715 railway cars, all but 35 are unusually heavy cars weighing 44,000 to 50,000 pounds each. Of these heavy cars 459 are equipped with four 50-horsepower motors, and 221 are equipped with four 40-horsepower motors. The 35 lightweight cars average approximately 29,000 pounds, and are equipped with four 25-horsepower motors. These weights may be compared with approximately 35,000 pounds for the average PCC car. Practically all of the heavy cars are equipped with field shunting devices which, while resulting in higher consumption of electricity, have resulted also in increasing our average speed. The average speed of our railway cars for 1938 amounted to 10.72 miles per hour, which according to the American Transit Association records was, I believe, third highest in the nation.

It is true that the heavy cars in use on this property were designed and built 20 or 30 years ago. They were not, however, designed and built as most of the older cars which have been and many of which still are in use on many of the transportation systems of this nation. They appear to have had points of design which still make them more acceptable to our patrons as comfortable-riding vehicles than most of the older cars of other systems to which we refer. Moreover, they have been maintained considerably above the average of those of other systems. They are clean, strong, and comfortable—somewhat noisy we grant—but on the whole the continued operation of these very cars we believe has been one of the factors which has kept our company on a basis of earnings which has made it possible to keep us paying our bond interest and out of receivership. We have every respect for the operation of the PCC car, and although we have had no experience here with it or with the operation of trolley busses, we can see the advantage of their use in certain fields. We are slow to be convinced that either of these types of vehicles can now be economically substituted for the operation of our present equipment. To do so would result in the destruction of a remaining value in our present equipment which we feel would not be compensated for in the new equipment. Moreover, our experience with our own lightweight cars makes us rather skeptical that the PCC car with its small wheels and relatively light weight can give adequate service during our winter months, bucking snowdrifts which accumulate here during these months and contending with the low temperatures which also contribute to the spinning of wheels and the slowing up of service. We have found our own lightweight cars to be inadequate in snowstorms and low temperatures, and conversely we have found that our heavy cars powered with 40- and 50-horsepower motors do maintain our schedules during winter months even though our wheel wear during these months averages six times as great as it does during the summer months of June, July, and August. Under the circumstances, therefore, it appears to us that the substitution of these new types of rolling stock for our present standard cars must be predicated upon our being relieved of the

expense of rebuilding of a substantial section of wornout track and paving in a particular route. Having such a route up for consideration, decision as to whether to substitute trolley busses or gasoline busses must rest upon the principles outlined by Professor Hoard in this paper.

While we may not agree that the time is ripe here for the substitution of some of the newer types of equipment, this very fact can be brought out most effectively by such an analysis as Professor Hoard has presented in this paper.

H. A. Perryman (nonmember; Los Angeles Railway Corporation, Los Angeles, Calif.): This paper has been developed with considerable labor and research and is based necessarily on assumed averages for various operating and traffic factors. As an academic study the paper shows considerable enterprise and has, in my opinion, a decided value in the field of research.

In general, these assumed averages do not apply to this property, with the result that the charts as developed cannot be applied to specific lines operated by the Los Angeles Railway.

The study is based on an average 6-cent fare which is higher than our average fare (4.51 cents) and an average speed of 13 miles per hour which is higher than our average rail speed (10.5). Rates of depreciation and interest are also different.

The study is also based on two assumed averages, which are not often found on our lines, namely L, or the average loading of vehicle, and m, or the ratio of the cars per hour in the peak to the average base cars. Table I of this discussion is a tabulation showing the values of L and m on our rail and principal coach lines.

The study is based on interest rates for new money only, and does not make any allowance for interest on tracks already in place and in good operating condition. As a result of this the values of A in the charts (PCC cars with no track rehabilitation) are somewhat delusive.

The study is based, of course, purely on engineering and/or accounting data and does not take into consideration the operating policy of the company or the popular requirements of the districts to be served.

In planning the modernization of a line or property, the nonengineering considerations, particularly public sentiment with regard to the choice of street car, trolley bus, or bus, are of primary importance.

George L. Hoard: There are in this country transit systems of almost all degrees of preservation. On some systems the equipment is old and run down, with very little useful life remaining. Contrariwise, on others the standards of maintenance are much above the average. Equipment that nominally belongs to a previous generation has been rebuilt one or more times, so that while its appearance may not compare favorably with the latest in modern vehicles, its operating characteristics and cost of maintenance may be reasonably satisfactory. The discussion by Mr. McWethy indicates very strongly that the property of the Twin City Rapid Transit Company falls in the latter class.

This diversity in the condition of present equipment and its associated variables makes it practically impossible to offer a general solution to the question of when will it be more economical to modernize a system or to keep the present equipment in service. Each specific case must of necessity be an individual problem. For this reason, attention is confined in the paper to the case where the present equipment has little useful life remaining.

However, the methods of analysis outlined in the paper are equally applicable where the present equipment may be in good repair. The decision here usually rests on more precarious ground, however, for the reason that if the new equipment is to show a better return than the old it must produce an increase in riding. This increase in riding must be estimated, which is a matter of personal judgment and hence somewhat uncertain at best.

The paper clearly indicates the value of an increase in patronage to a transit system. It also suggests the importance of fast, frequent service with attractive vehicles in encouraging riding. Mr. Josephs, in his discussion, points out the importance of merchandising transportation. Undoubtedly much more attention will be paid to merchandising of transportation in the immediate future. In this respect, the advantages are with modernization. It is much easier to sell transportation with modern streamlined vehicles than with their predecessors. As pointed out in the paper, in many instances where modernization has taken place the results have been so successful that it would have been possible to "write off" considerable in the value of the present equipment and still show a satisfactory financial return.

The figures from the Los Angeles Railway submitted by Mr. Perryman are both interesting and instructive. In general, the value of m will depend to a considerable degree upon community characteristics; for example, a city that is highly industrialized would normally have high peak loads. However, the values quoted are, with a few exceptions, about as one would expect; namely, one or slightly over, for the very light lines, around two or better for the lines of intermediate traffic, while on the heavy lines the value of m is again lower, approaching an approximate average of 1.7.

The value of L, as would be expected, varies over a considerable range being generally low on the light short lines and much higher on the long heavy ones where there would naturally be much local riding.

The figures quoted are particularly interesting in that they illustrate the wide variation in conditions that may obtain on the different routes of a single system, especially if it be a large one. They also indicate the possible danger, as suggested by Mr. Woods, of drawing too general conclusions from specific examples. They further point the necessity for individual study of each line if a complete picture is to be obtained.

Table I. Los Angeles Railway Corporation—Passengers Carried, Load Factors, and Equipment Requirements

	Miles of Route (One Way)	Passengers Carried in 1938 (Thousands)	Passengers Per Mile of Route (Thousands)	Passengers Carried Daily	Number of Trips Daily	Number of Seats	Value of L	Value of m
Rail lines								
A	9.36	9,786	1,046	23,118	396	48	1.2	1.9
B	10.06	10,594	1,053	29,263	356	48	1.7	1.9
D	3.13	1,998	638	4,905	210	44	0.5	1.0
F	12.92	7,736	599	18,073	312	44	1.3	1.8
H	9.62	9,088	945	24,027	403	48	1.2	1.6
I	1.51	609	403	1,360	202	34	0.2	1.0
J	12.54	15,310	1,221	42,690	470	59	1.5	1.6
K	6.44	1,809	281	4,609	156	44	0.7	1.0
L	11 01	12,132	1,102	27,326	409	48	1.4	2.0
N	4.94	6,106	1,236	18,934	326	48	1.2	1.9
O	9.04	6,896	763	16,270	264	44	1.4	1.5
P	10.06	25,877	2,572	63,447	637	59	1.7	1.7
R	11.14	15,397	1,382	38,559	503	48	1.6	1.4
S	12.42	18,163	1,462	42,567	518	48	1.7	1.6
U	13.02	16,675	1,281	43,286	424	44	2.3	1.5
V	12.05	15,585	1,293	36,821	500	48	1.5	2.4
W	15.70	17,605	1,121	45,081	569	48	1.7	1.8
2	6.81	2,816	414	6,636	232	44	0.7	1.1
3	7.00	12,280	1,754	28,293	498	53	1.1	2.0
5	21.80	16,420	753	39,948	508	52	1.5	1.9
7	9.63	8,765	910	21,622	379	48	1.2	1.9
8	8.15	6,863	842	19,028	366	44	1.2	2.1
9	8.37	6,089	727	14,611	325	48	0.9	2.1
10	9.93	5,917	596	13,934	263	44	1.2	1.4
Coach lines								
Through coach lines								
44 Beverly Blvd	9.19	4,693	511	13,300	478	40	0.7	2.3
47 East 9th-Whittier	7.55	1,700	225	5,700	284	30	0.7	2.1
49 Figueroa	7.22	1,136	157	3,400	210	30	0.5	1.8
Cross-town lines								
41 Alvarado	3.36	2,752	819	7,300	292	30	0.8	1.6
50 Florence-Soto	13.94	7,517	539	21,600	377	30	1.9	2.0
54 Manchester	11.57	1,125	97	3,600	126	30	1.0	1.0
Intermediate lines								
55 Maywood-Bell	7.55	1,747	231	5,200	223	30	0.8	2.0
64 Highland Park	5.97	1,414	254	4,600	195	30	0.8	1.2

L—Average loading of vehicle, that is, the ratio of the average number of passengers per trip to the vehicle seating capacity, in decimals.

m—Ratio (in decimal) of the cars per hour on the peak to the average or base cars per hour.

Power Supply for Resistance-Welding Machines

Foreword

OWING to the tremendous increase in the use of the resistance-welding process during the past several years, and the magnitude of many of the more recent installations, the problem of power supply for these operations has become one of primary importance to all concerned. Resistance-welding machines present an electrical load of intermittent character, high magnitude, and extremely poor load factor, and because of these poor inherent characteristics, the providing of adequate electric service, both from the standpoint of plant electrical distribution and the power system supply, involves special considerations and methods.

The AIEE subcommittee on power supply for welding operations with members representing manufacturers, users, power companies, and the American Welding Society, has been actively studying the various phases of the problem with the fundamental aim in view of bringing about a closer relationship and better spirit of co-operation between these groups in order that each will better understand the problem from the other's viewpoint.

From the viewpoint of the power companies and users, it has been difficult in the past to obtain adequate and reliable engineering data on proposed welder installations prior to their actual installation and operation and, in addition, some of the machines had exceedingly poor electrical characteristics. From the viewpoint of the manufacturers and users, there have been instances where they have been unable to get proper service connections from the power company for handling welder loads. Such refusals to provide service were, no doubt, justified in some cases but others may have been due simply to a lack of interest in the load by the power company and a concern that the load might be disturbing to other customers. Sometimes the user has not adequately prepared for the welder load by the installation of proper bus and transformer facilities with the result that welds are poor and results inconsistent. It is certain that many of these cases of poor co-operation and unsatisfactory installations have been due to a lack of knowledge of all the pertinent facts.

The subcommittee has been working for some time on a series of three reports covering the various phases of the general problem of electric service for resistance welders; two of these are presented herewith:

I. Guide to good electrical performance of resistance-welding machines

II. Resistance-welder installations

Under preparation is:

III. Factory wiring for large resistance welders

It is the hope of the subcommittee that these reports will assist, at least in some small measure, power engineers, industrial plant engineers, welding machine engineers, and any others actively interested in resistance welding in the planning of layouts for welder installations and also in the purchase of new equipment.

Papers 40-57 and 40-58, prepared by the subcommittee on power supply for welding operations of the AIEE committee on electric welding, recommended for publication by the AIEE committee on electric welding, and presented at the AIEE winter convention, New York, N. Y., January 22–26, 1940. Manuscript submitted November 27, 1939; made available for preprinting January 4, 1940; released for final publication February 26, 1940.

Personnel of AIEE subcommittee on power supply for welding operations: L. W. Clark, *chairman;* E. F. Dissmeyer, M. B. Gathman, C. E. Heitman, W. F. Hess, E. A. Hester, H. S. Hubbard, S. M. Humphrey, A. H. Lewis, G. S. Mikhalapov, C. L. Pfeiffer, F. H. Roby, and F. E. Sanford.

I. Guide to Good Electrical Performance of Resistance-Welding Machines*

Purpose of Report

Resistance welding consists of clamping two or more pieces of metal between electrodes and passing electric current through them for the purpose of joining the pieces by fusion of the metal. The adequacy of supply and proper control of this electric current are determining factors in the production of consistently good welds. Relatively high values of current are required at the weld, and the electrical characteristics of the welding machine determine the amount of current which must be drawn from the electric supply lines when delivering these high values of welding current. An efficient machine of good electrical characteristics and low kilovolt-ampere demand requires a much smaller plant investment for transformers, feeders, etc., than the machine with poor electrical characteristics and resulting high kilovolt-ampere demand, although both may deliver the same welding-current output.

* Paper 40-58.

This report shows what is meant by good electrical performance and outlines factors upon which good electrical characteristics are dependent. A better understanding of what constitutes such good characteristics will bring about a better appreciation of them by the users of the equipment. Concurrently, as the art advances and the demand for improved designs increases, the manufacturers will meet these demands with continued improvements in their machines. There are several recent developments that eventually may result in radical reductions in demands of resistance welders and a resultant easing of the power-supply problem, but until such machines are commercially and economically available, a thorough understanding of the electrical characteristics of the present-day conventional machines is necessary if they are to be economically served.

It is intended that the report shall assist the purchaser in the preparation of specifications for the purchase of welding machines of the best electrical design, thereby minimizing the problem of power supply. Among the more common types of machines to which it applies are spot, projection, butt, flash, seam, and portable welders.

The report has been made very general in nature and to all who are closely associated with the electrical industry, it may appear that too many elementary factors are discussed, but to production and industrial engineers who represent perhaps the largest single group interested in welding as a production tool, the report should fill a long-felt need in acquainting them with the electrical problems associated with resistance welding.

Scope of Report

The report covers the following subjects:

1. Electrical characteristics of welding machine:

(*a*). Kilovolt-ampere demand
(*b*). Kilowatt demand
(*c*). Power factor
(*d*). Heating
(*e*). Welder primary voltage

2. Power supply and its effect upon welder performance

3. Secondary circuit of welding machine

4. Welder transformer

5. Control equipment

6. Name-plate data for welding machine

Electrical Characteristics of Welding Machines

The electric current required at the weld is supplied by means of a welding transformer which reduces the supply or plant voltage to a relatively low value (usually less than 20 volts). By this method the current from the supply lines is stepped up to the high value required for welding. The magnitude of actual welding current required depends upon many interrelated factors, such as the type of weld, material being welded, the geometry of the pieces, applied pressure, time of current flow, and perhaps others, all of which are beyond the scope of this report.

The current drawn from the supply lines, while also dependent upon these same factors, is in addition greatly affected by the design and physical arrangement of the welding machine itself. The ratio of the welding or secondary current to the supply or primary current is the best relative measure of the desirable electrical characteristics of two machines of the same secondary current output and the same primary voltage rating. The higher this ratio, the more desirable will be that particular machine, other factors being equal.

Kilovolt-Ampere Demand

The kilovolt-ampere demand is the primary or supply current multiplied by the rated primary voltage and is also approximately equal to the secondary current multiplied by the open-circuit secondary voltage. (The kilovolt-ampere demand as used here in referring to the machine is the instantaneous demand as measured by an oscillograph and should not be confused with the integrated demand of the power meter used for billing purposes.) It bears no relation to the kilovolt-ampere rating of the welding transformer except that it will usually be somewhere between one to about six times as great.

The kilovolt-ampere demand is a direct measure of the desirable electrical characteristics of the machine design—the greater the kilovolt-amperes, the poorer the machine for equal outputs of secondary current.

The kilovolt-amperes taken by a given welder will be a maximum when the electrodes are short-circuited and when the voltage taps are set to give the maximum secondary voltage. When the machine is actually welding, the kilovolt-amperes will always be less than the short-circuit maximum because the impedance of the material being welded causes a reduction in secondary current. If the material being welded is nonmagnetic and of low resistance, such as copper or aluminum, the short-circuit condition is rather closely approximated.

Kilowatt Demand

The kilowatt demand of a welder reveals very little regarding the machine characteristics. (The kilowatt demand as used here in referring to the machine is the instantaneous demand as measured by an oscillograph and should not be confused with the integrated demand of the power meter used for billing purposes.) It represents the energy component of the kilovolt-ampere demand.

Power Factor

The power factor is the ratio of the resistance to the impedance of the welding machine and is also equal to the kilowatt demand divided by the kilovolt-ampere demand. In general, the power factor of a welder should be as high as possible commensurate with satisfactory welding performance. Usually the more efficient and better designed machines will have higher power factors accompanying lower machine impedances and lower kilovolt-ampere demands.

However, high power factor in itself is not necessarily a guarantee of an efficient machine. With the welding electrodes short-circuited, the impedance of the machine measured at the primary terminals of the welding transformer should be as low as possible. This impedance is composed of resistance and reactance and can be reduced by reducing either or both of these quantities. If both are reduced in the same proportion, the power factor will remain unchanged. If the reactance is reduced and the resistance is kept the same, the over-all impedance will be reduced and the power factor increased. On the other hand, if the reactance is not changed and the resistance is increased, the power factor will be increased, but also the over-all impedance will be increased and the efficiency reduced which is highly undesirable. It is, therefore, insufficient to state merely that the machine power factor should be high, because the high power factor might be obtained by the latter method mentioned above. High power factor is advantageous only when accompanied by low over-all impedance and obtained by reduced reactance rather than increased resistance.

The approximate power factor of a machine must be known when calculating the voltage regulation of the electrical supply system due to the welder operation. However, an accurate knowledge of the maximum kilovolt-amperes drawn by the welder is of much more importance than an accurate knowledge of the power factor ratio and, in general, results obtained when using estimated power factors are reasonably satisfactory.

Tests of many flash, butt, spot, and projection welders show that the usual range of power factors for the larger machines (50-kilovolt-ampere rating and up) is between 20 and 40 per cent, and that for estimating purposes the use of 30 per cent power factor, coupled with the known value of kilovolt-ampere demand, will prove reasonably accurate. Similarly, 40 per cent power factor can be used for machines of 10- to 50-kva rating, and 60 per cent power factor for machines under 10 kva in size.

Heating

The heating of the machine is another important consideration due to the fact that the insulation life of the welding transformer is a function of operating temperature. The manufacturer shall provide ample cooling of transformer and secondary loop to prevent overheating at the rated current and duty cycle of the machine. (The duty cycle is the per cent of time that current flows, averaged over a definite period. The length of the period depends upon the class of equipment and is, for example, one minute for electronic control devices.) A duty cycle of 50 per cent has been adopted as standard for rating purposes and the transformer kva rating is an indication of the allowable heating load for which the machine is designed.

Welder Primary Voltage

If possible, the larger welding machines should be supplied from 440 or higher voltage sources due to the fact that the primary current demand is inversely proportional to the primary voltage, everything else being equal. The use of higher voltages assists in keeping voltage drop or regulation at a minimum.

Power-Supply Requirements and Welder Performance

Allowable voltage drop rather than allowable heating usually becomes the limiting factor in determining supply conductors and transformers because of the extremely low operating duty cycles of most welding operations. The supply to the welders should be such that the maximum voltage fluctuation or dip, measured at the last point on the welder bus or distribution wiring which is com-

mon to two or more machines, does not exceed 10 to 15 per cent. (This value of 10 to 15 per cent applies to the welding circuit and is not to be confused with the usual limitation of one to two per cent for lighting circuits affected by the welding load.) It is highly desirable to provide a system which will keep the voltage fluctuation within the ten per cent limit if consistently good welds without an excessive number of rejects are to be expected. In extreme cases the 15 per cent limit might prove satisfactory, and there are conversely some few applications in which the ten per cent limit might be excessive.

The nominal base voltage may vary gradually from time to time throughout the day due to general plant load changes and other factors, and no attempt is made here to specify an allowable range for this gradual shifting of the base voltage. Obviously, if the gradual change is appreciable from, say the day operating shift to the night operating shift, it might become necessary during such periods to change the heat or tap setting on all welding machines to compensate for the changed voltage conditions.

This report does not concern itself with the methods of providing service for welders, except to show the importance of keeping the kilovolt-ampere swings or instantaneous demands at a minimum. A succeeding report entitled "II. Resistance Welder Installations" describes the various commonly used methods of providing service for welders.

Small welder installations are usually served by a power company at either 220 or 440 volts, and the minimum charge for service may be roughly proportional to the magnitude of the maximum kva swing or instantaneous demand and, consequently, it is much to the advantage of the user to purchase a machine with as small a demand as possible.

Welder installations in the large factories, which either have their own power plants or are served by a power company at primary voltages, such as 2,300, 4,800, 6,600, or 22,000 volts, present a similar service problem with the exception that the plant engineer is directly concerned with transformer and distribution bus investment costs needed for the welders.

To show the importance of purchasing a welder of good electrical design, a typical example will be worked out. The welding engineer of a certain plant needs a projection welder with a maximum welding-current output of 100,000 amperes. He gets quotations from different manufacturers on machines incorporating the desired mechanical and control features for handling the particular type of work involved. The final selection eventually is between two competing machines, each having the same mechanical features and same method of control, but with the following differences in electrical rating:

	Machine A	Machine B
Rated kilovolt-amperes of transformer (50 per cent duty cycle)	300	500
Maximum open-circuit secondary voltage—volts	12	20
Maximum secondary current (maximum secondary voltage and minimum throat spacing)—amperes	100,000	100,000
Rated primary welder voltage—volts	440	440

Welder B was slightly more expensive than welder A but the fact that it had a larger transformer at first glance indicated it to be the best machine. However, a true analysis of the cost of serving the two welders shows that welder A is the logical selection. The basic consideration as far as welding ability is concerned, is the secondary current output and the ability of the welder to operate without overheating at a certain prescribed rate of production or duty cycle. Both welders had the same maximum current output and the productive output was guaranteed the same by both manufacturers. The larger transformer simply was needed to supply the excessive losses of machine B. The approximate kilovolt-ampere input for machine A is:

$$\frac{(100{,}000 \times 12)}{1{,}000} = 1{,}200 \text{ kva}$$

and for machine B is:

$$\frac{(100{,}000 \times 20)}{1{,}000} = 2{,}000 \text{ kva}$$

Assuming that a 1,200-kva step-down power transformer is needed to serve welder A, it would be necessary to go to a 2,000-kva transformer for machine B for the same voltage regulation. At \$3 per kilovolt-ampere, this amounts to \$2,400 added investment for machine B in transformer capacity alone. Conductor costs for bus and distribution are correspondingly greater for the machine with the higher kilovolt-ampere input. The plant engineer who is responsible for costs of service for the welding operations will certainly select welder A as the most economical and desirable machine. The welding engineer who is interested primarily in machine output and production, is equally satisfied as both machines are equal in this respect.

In addition, there is always an upper limit of allowable kilovolt-ampere demand, the exact magnitude depending either upon the factory's location with respect to the power company's substations and power lines or the size of its own generating plant.

In case of power company service, the point of connection to the power company's system determines the allowable size of welder that can be handled. The sudden flow of welder current through the system impedance causes a momentary voltage fluctuation which, if of sufficient magnitude, results in lamp flicker for all lighting customers at that and nearby locations. The farther the point of service is from the main generating plants and larger substations, the greater the system impedance and resultant voltage fluctuation for a given size welder. Voltage fluctuations must be kept within accepted limits for lighting customers. These limits vary, depending upon the frequency of the fluctuation and, in some cases, if the frequency is high, such as with certain types of seam welders, the allowable voltage fluctuation may be as low as one-half volt at the lamp, and for ordinary frequencies experienced with spot, projection, and flash welders may be as high as one and one-half to two volts.

Whenever the kilovolt-ampere demand of the welder is great enough to cause lamp flicker at other nearby customers, there are only two fundamental changes which can be made to eliminate the flicker. The system impedance beyond the point of service common to the lighting and welder loads can be reduced or the sudden flow of current through that impedance can be reduced. There are numerous methods for accomplishing either of these changes, such as reducing the system impedance by increasing substation and line capacity, tapping the welder load direct to the transmission system, separating the lighting and welder loads and serving them from separate substation bus sections, or reducing the amount of current by the use of series capacitors, synchronous condensers, phase balancers, or motor generator sets. Most of these methods involve expense of some considerable magnitude which must be passed on to the user of the welder. Obviously, if the purchaser of the welder can select a machine of more efficient design with a kilovolt-ampere demand within the allowed limit for that particular location, such expensive power-

system changes or the addition of corrective equipment would not be needed. It is, consequently, much to the advantage of the prospective purchaser of the welder to obtain in advance of the purchase the allowable maximum kilovolt-ampere demand that the power company can permit at that location and then, if at all possible, select a machine that will produce the desired welding current without exceeding this allowable kilovolt-ampere input.

Welders of large size can usually be served readily in large industrial areas which generally have concentrations of power quite separate from any lighting services. The main business sections of large cities do not usually have distribution facilities suitable for welders and generally the cost of providing service at such locations is prohibitive even for relatively small machines. Suburban areas and small towns are also very likely to be unsatisfactory and expensive locations except for the smaller machines.

Secondary Circuit of Welding Machine

The single, most important factor in keeping the kilovolt-ampere demand low is the design of the secondary circuit of the welding machine regardless of whether it is a spot, seam, or other type of welder.

In order better to understand why this is so, it is only necessary to consider from the fundamental angle what is required to make a given weld. As a simple illustration, suppose a welding machine is required to spot weld two pieces of 16-gauge SAE 1010 cold-rolled steel. From existing engineering records the design engineer would possibly conclude that to obtain the desired quality weld, it would be necessary to limit the time to eight cycles and to pass 12,000 amperes through the parts to be welded.

The next point to be considered is the geometry of the parts to be welded since they, in turn, will dictate the minimum clearance in the secondary circuit of the welding machine which will permit properly placing the parts to be welded between welder electrodes. In this case, perhaps a 12-inch throat depth and 7-inch clearance between horns would readily admit the work to be welded. The next step is to determine the voltage necessary to cause the required 12,000 amperes to flow through this 12-inch by 7-inch secondary circuit with the work in position. This voltage might be found to be four volts which would immediately establish the kilovolt-ampere demand of 48 kva. If, on the other hand, a machine had been selected with a throat depth of 24 inches and a horn clearance of 12 inches because it looked as though it was plenty big enough for the work and would also permit welding a larger job at some future date, a voltage as high as ten volts might have been required to give the 12,000 amperes, thereby imposing a demand of 120 kva on the distribution system and penalizing everyone concerned forever after.

From this it may be concluded that the first rule in obtaining a machine with a minimum demand for a given welding operation is to pick out a machine with a clearance that is just large enough for the work to be done, fully recognizing the fact that if any larger clearance exists, the demand is going to be larger than it need be. There are, of course, cases where the user definitely has need for a larger throat for a certain portion of his work and he must then either put up with a larger than necessary demand on smaller parts or perhaps purchase two machines.

Having determined the throat clearance which is to be furnished in the machine, there are other factors which influence the demand, such as the actual design of the machine having this throat depth. These matters are entirely in the hands of the welding-machine manufacturers and it may be said that they, as a group today, are doing their utmost to reduce the impedance of their welding machine circuits in order to reduce to a minimum possible voltage disturbances in plant-distribution and power-system lines.

The prospective purchaser of welding machines can be assured of the merit of the electrical design of the machine being purchased, by comparing the secondary current outputs and the kilovolt-ampere inputs of the machines being considered. For the same secondary current output the machine having the lowest kilovolt-ampere input will be the lowest impedance machine and, consequently, the most desirable from this angle. The purchaser can also observe the physical geometry of the welding machine parts and select a machine in which the transformer is placed as close to the useful throat of the machine as possible and in which the flexible connections are so arranged as not to introduce excessive reactance.

Portable Welders

In the case of portable welding machines, the same fundamental principles apply. There is here, however, another factor to be considered and that is the type of cable used between the transformer and the gun, assuming, of course, the same principles regarding clearances have been applied to the gun as were mentioned above in regard to the throat of the welding machine. Here it is important that (1) cables no longer than necessary are selected, (2) that in the case of parallel conductors, cables be strapped closely together at all times to reduce the reactance, and (3) that full consideration be given to single, low reactance, interleaved, and concentric designs of cable which are now on the market and which substantially reduce the demand during weld.

Welder Transformer

The transformer incorporated as part of the complete welding machine should be built in accordance with the latest revision of the AIEE Standards No. 39 as soon as this revision can be accomplished. In the meantime the latest Resistance Welder Manufacturers Association Standard, which is a carefully drawn one, can be relied upon. The transformer name-plate rating is based upon a 50 per cent duty cycle and indicates the kilovolt-ampere load it can safely carry at 50 per cent duty cycle. It in no way indicates either useful output of the machine in welding current, or the maximum kilovolt-ampere input to the machine from the supply lines. The equivalent continuous ratings corresponding with loads at various duty cycles are:

70.7 per cent of the load at 50 per cent duty cycle

31.6 per cent of the load at 10 per cent duty cycle

22.4 per cent of the load at 5 per cent duty cycle

Control Equipment

Proper control of a welding machine is essential if consistently good results are to be obtained. Many pages would be required to cover adequately and completely all the various phases of welding-machine control. It is the intention here to simply outline in as concise a manner as possible the fundamental concepts of control requirements, the various types of control equipment, and the field of application for each.

Fundamental Requirements

The energy required to produce a weld is directly proportional to the current squared, the resistance of the weld area between the electrode points, and the time during which the welding current is allowed to flow. To obtain consistent

results, each of these three factors must be controlled as carefully as possible.

The welding current is usually regulated by changing the position of a tap switch on the primary side of the welding transformer or by delaying the ignition of electronic interrupters, thereby reducing the effective voltage applied to the transformer primary. In any case the transformer secondary voltage is raised or lowered to bring about the required change in current.

Contact resistance varies inversely with the pressure applied to the work. On manually-operated or motor-driven machines a limit switch can be set to close at a point equal to satisfactory welding pressure. Operation of the limit switch would initiate the flow of current. The pressure switch, actuated by means of the back pressure built up in the operating cylinder, is usually substituted for the limit switch on air-operated machines. However, an adjustable time delay introduced between the operation of the air valve and the application of power to the work, would accomplish the desired result.

Timing of the interval during which current is allowed to flow is a more difficult problem. Many types of equipment are available for this purpose. In general, the complete installation consists of an interrupter for the power line and some means for predetermining the period during which it is closed.

Types of Equipment

The interrupter may be electronic, motor-driven, air operated, or magnetically operated. To apply recently adopted standard rating curves in the selection of interrupting equipment, it is essential that these factors be known:

1. Transformer maximum primary amperes
2. Required number of welds per unit of time
3. Estimated length of each weld

Control devices are classified as two different types—synchronous and nonsynchronous. The first is generally used where a premium is placed on absolute accuracy. High initial cost and relative complexity discourage universal use.

Nonsynchronous control involves an inherent possible error amounting to at least a plus or minus one-half cycle and possibly more, depending upon the nature of the equipment. In addition, it does not guard against the danger of variable transient current surges introduced by haphazard circuit closing present in nonsynchronous control. These errors become objectionable when applied to short timing periods and when the nature of the work is such that precision control is necessary. The fabrication of extremely small parts and the welding of stainless steel or nonferrous metals are usually within this classification.

A design classification for timers would include mechanical, electromagnetic, electrostatic, or electronic types. Final selection of a specific device should be based on the accuracy required, initial cost, maintenance cost, accessibility, range of adjustment, reliability, and simplicity.

Either the "fixed" or "current responsive" principle of current timing may be used. "Fixed timing" is satisfactory for most applications and results in less complicated equipment. Some few types of work require automatic compensation for variations in work conditions and "current responsive" systems are available for these. The machine supplier or control manufacturer will be acquainted with these requirements.

When air-operated machines are equipped with solenoid-operated valves, a fully automatic timing device performing the following functions can be used:

1. Automatic application of pressure to the work
   (Squeeze Period)
2. Initiation of power flow at time interval later
   (Weld Period)
3. Termination of power flow at the conclusion of the weld
   (Hold Period)
4. Removal of pressure after the weld has cooled
   (Off Period)
5. Reapplication of pressure after the work has been removed and new parts placed between electrodes

A low-voltage (110 volts or lower) push-button circuit is recommended to minimize danger of electrical shock.

If the voltage regulation in the welder supply lines is excessive, a separate supply line for the timer control circuit should be installed. A 110-volt lighting supply circuit is usually available for this purpose. The installation of a fusible control circuit disconnect switch separate from the power switch is considered an operational advantage although separate power and control sources are not always required.

Name-Plate Data for Complete Welding Machine

Power and industrial engineers have been handicapped in the past when called upon to plan and provide service for proposed welder installations because of a dearth of reliable and accurate information regarding name-plate and specification data for the proposed machines, particularly information about maximum kilovolt-ampere demand or load. To improve this situation the following name-plate data should appear on the name plate of the complete welding machine:

1. Manufacturer's name and address
2. Manufacturer's type and designation number
3. Rated kilovolt amperes of transformer (50 per cent duty cycle)
4. Maximum open-circuit secondary voltage
5. Minimum open-circuit secondary voltage
6. Maximum secondary current (with maximum secondary voltage and minimum throat spacing)
7. Rated primary voltage and frequency
8. Manufacturer's serial number

From the above essential name-plate data, the following additional information can be readily calculated:

(*a*). Transformer turn ratio [rated primary voltage (7) divided by maximum open-circuit secondary voltage (4)]

(*b*). Maximum kilovolt-ampere input at rated voltage (neglecting exciting current) [Maximum secondary current (6) multiplied by maximum open-circuit secondary voltage (4)]

(*c*). Maximum primary-current demand (neglecting exciting current) [Maximum secondary current (6) divided by transformer turn ratio (*a*)]

II. Resistance-Welder Installations*

Purpose of Report

Factory wiring and electrical distribution for resistance-welding loads must be designed on an entirely different basis than that for the ordinary power and lighting loads encountered in industrial plants. To provide a sound basis upon which recommended methods of wiring, types of bus construction, and transformer arrangements can be established the AIEE subcommittee on power

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* Paper 40-57.

supply for welding operations has obtained descriptive reports of a number of commercial resistance-welder installations, in plants throughout the country. These reports show the different methods successfully employed in existing installations, and give a clear picture of some of the problems involved. It is hoped that they will serve other users of resistance-welding equipment as a basis upon which new installations can be made.

Design Principles

In reviewing these reports, it should be remembered that the majority of resistance-welding machines have instantaneous kilovolt-ampere demands several times their normal rating, and that in order to prevent excessive voltage drop at this equipment, as well as at any nearby equipment, the supply and distribution facilities must be designed on the basis of the peak kilovolt-ampere demand rather than the normal rating of the machine. From a standpoint of voltage regulation the supply and distribution system must be such as would normally be employed if this peak kilovolt-ampere demand were drawn continuously. However, due to the low operating duty cycle of this load, its heating effect on the system is usually extremely small.

Since the capacity of all power equipment and distribution systems is based on heating or temperature-rise limitations it is seen, therefore, that in order to serve one resistance-welding machine, the normal capacity of the system must be much higher than necessary from a heating standpoint in order to satisfy the conditions of voltage regulation. In fact, in designing a system to supply two or three or even ten welding machines operating on the usual duty cycle encountered, it is safe to neglect the consideration of heating capacity required and design the system to satisfy the consideration of voltage drop. It is only when a considerable number of machines are involved on a single system that the heating becomes a consideration of any importance, or when the duty cycle of a single welder exceeds about 25 per cent, such as with most seam welders.

Summary

In the following representative welder installations, several types of feeder distribution systems are represented. Two of the companies employ a bus system to which the individual welders can be readily and quickly connected or disconnected. Tap points are available at regular intervals and the welding machines can be moved around from season to season with very little expense. The same is true, to a lesser degree, of the wire or cable feeders used by the other companies. This type of feeder does not lend itself quite so readily to frequent changes in plant layout, but is generally cheaper and easier to install.

The bus system employing the concentric arrangement of copper tubes will be found to have the lowest voltage drop, and where this factor is of major consideration this type of feeder is of highest efficiency. In installations where the equivalent thermal loading is high, this type of construction may be unsatisfactory since the heat radiation or conduction from the inside conductor is comparatively low. However, should it become necessary, cooling air can be forced through the inner conductor thus raising its load capacity. The system of interlaced copper bus bars, usually has a high load capacity, but gives a slightly higher voltage drop than the concentric construction.

The system of cable construction is of course the simplest, since the problems of insulation are minimized. In general this type of construction gives a higher voltage drop and lower load capacity than either of the above types. However, if the various conductors are interlaced and spaced very close together the voltage drop can be reduced to a value comparable with the bus-type construction. In so doing the load capacity is reduced due to the reduced radiating surface, and this must be compensated for by a sufficient number of parallel lines to reduce the thermal loading to the safe point.

Table I shows the ratio of total connected welder load to total supply-transformer capacity for the various installations, the ratio of largest single welder to total supply-transformer capacity, and the ratio of resultant thermal load to total connected load. The first ratio in some cases may be determined by the thermal loading of the system and thus be dependent upon the average operating duty cycle of the units comprising the installations. If the average operating duty cycle is high, the thermal loading will be high and this ratio must be low. The ratio of largest single unit to supply-transformer capacity is usually determined by the requirements of over-all voltage drop. If a large part of the permissible voltage drop is consumed in the feeder line, the allowable drop in the supply transformer is small, and this ratio must be small. In most commercial installations it is this consideration of voltage drop that determines the supply-transformer capacity, rather than the consideration of thermal loading.

It will be noted that the ratio of total connected load to total supply-transformer capacity varies from 0.4 to 8.74, but the weighted average is about 2.0. This wide variation may be partly explained by the fact that the method of rating resistance-welding equipment has, in the past, been rather vague, and the values of connected load taken from the name-plate ratings may be

Table I. Summary

Company	Feeder	Phases	Power-Transformer Capacity	Connected Load	Type of Service	Ratio Total Connected Load to Total Supply-Transformer Capacity	Ratio Largest Single Welder to Total Supply-Transformer Capacity	Ratio of Thermal Load to Total Connected Load
A		Three	3,000	4,500	Flash	1.5	0.25	0.118
B	*A*	Single	1,000	2,000	Projection, flash, and seam	2.00	0.50	0.10 for all feeders combined
B	*B*	Single	2,000	1,700	Projection and butt	0.85	0.375	0.10 for all feeders combined
B	Top	Single	2,000	1,960	Flash and projection	0.98	0.3	0.10 for all feeders combined
B	Center	Single	2,000	2,750	Flash and projection	1.375	0.3	0.10 for all feeders combined
B	Bottom	Single	2,000	1,250	Projection and flash	0.625	0.3	0.10 for all feeders combined
C		Single	1,500	13,119	Miscellaneous	8.74	0.3	0.048
D		Three	1,000	1,500	Seam	1.5	1.5	0.67
D		Single	1,260	500	Projection	0.4	0.4	0.44
D		Single	840	750	Spot	0.89	0.89	
E		Single	666	1,565	Spot and seam	2.35	0.60	
F		Three	1,500	2,400	Miscellaneous	1.6	0.267	0.177

quite at variance with the now commonly accepted practice of rating equipment on the basis of a 50 per cent duty cycle. For example under company *C*, section 6, we see that a normal current of 300 amperes applies to four different sizes of equipment, namely 50, 75, 100, and 150 kva.

The minimum value of 0.4 applies to a projection welder operating from a special supply transformer, and supplied by means of a concentric-cable feeder. Obviously the major consideration in this case is that of voltage drop.

The maximum value of 8.74 applies to an installation having a relatively large number of units. In such an installation the probability of a large number of units operating simultaneously is rather remote, so that from a standpoint of voltage drop, the required capacity of the supply-transformer bank is determined by the size of the largest single unit. In this instance the ratio of largest single unit to supply-transformer capacity is 0.4.

Another factor which makes for low supply-transformer capacity, in this case, is the use of the low-impedance concentric tubular bus. This type of bus gives a comparatively low voltage drop, so that a higher impedance (lower capacity) supply-transformer bank can be tolerated. The chief reason for the ability of company *C* to serve 13,119 kva of welding load with only 1,500 kva of supply-transformer capacity, is their use of a good concentric bus design with extremely low impedance. This permits serving an exceptionally large factory area by the single-bus system without obtaining excessive voltage drop at the welding equipment. Other types of bus construction and cable assemblies cannot serve as large an area, nor as many units, without excessive voltage drop. The result is that where such construction is used there must be more feeders operating in parallel or a higher supply-transformer capacity.

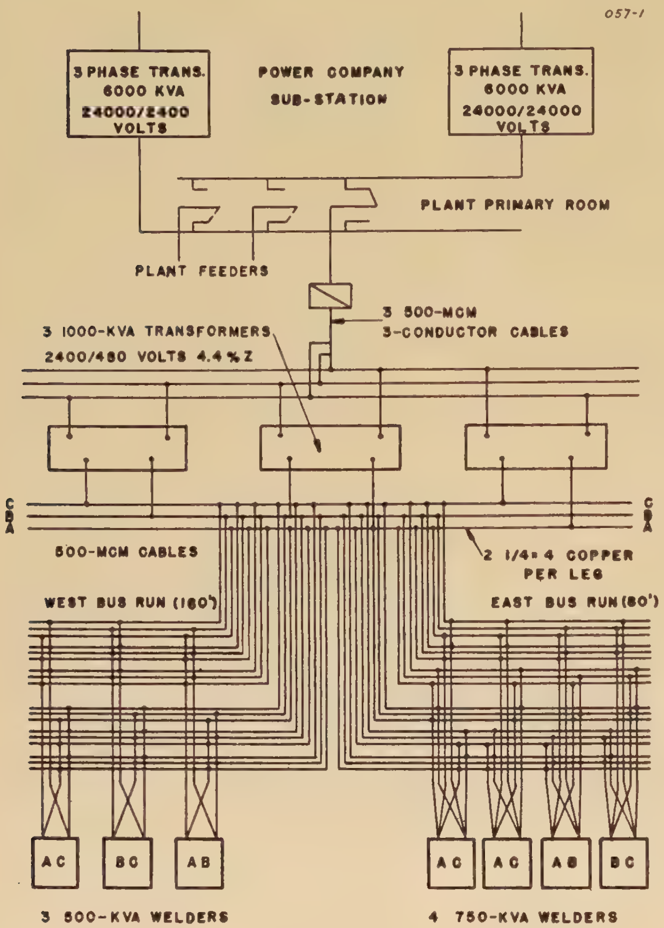

Figure 1. Schematic diagram of welder supply system—company A

Where a large number of smaller units are to be served, the thermal loading of the supply transformers and feeder lines may become the determining factor. This determination, however, depends upon a knowledge of the operating duty cycles of the various equipments. In this particular case the average operating duty cycle is comparatively low, the ratio of average kilovolt-ampere load to connected kilovolt-ampere load being 4.8 per cent. The ratio of average kilovolt-ampere load to supply-transformer capacity is approximately 0.4, the extra capacity being necessary to limit the voltage regulation.

The ratio of largest single unit to supply-transformer capacity varies from 0.3 to 1.5, with a weighted average of about 0.5. The maximum value of 1.5 applies to a seam-welder installation in which the thermal loading of the system is the determining factor in selecting supply-transformer capacity.

The ratio of thermal load to total connected welder load for these commercial installations of all types except seam welders is between 0.048 and 0.177, and for seam welders, between 0.44 and 0.67.

It must be remembered that it is impossible to give any definite empirical values for any of these ratios, since the proper values depend upon individual conditions. The values given in table I do, however, give a general idea as to the practice followed in some of the industry's successfully operating installations.

It is interesting to note that in all of these installations overload protection of the feeders and transformers is confined to instantaneous overcurrent devices, designed to protect against short circuits. In one installation this instantaneous tripping is reduced well below the short-circuit current to provide a measure of protection against high overloads on individual welders. The protection thus afforded against individual machine overloads is very small. In so far as we are informed, the only practical overload protection is that afforded in the connections to each individual machine. This may take the form of instantaneous overcurrent trips, overtime trips, or a combination of these two, or some thermal relay or fuse with thermal characteristics similar to the equipment to be protected.

For the protection of supply transformers, the instantaneous overcurrent devices set for short-circuit currents have proved satisfactory. In installations where the thermal loading is high, contact-making thermometers immersed in the cooling oil have been employed to trip the circuit breakers when the oil temperature becomes excessive.

Another point of interest is that the power supply for the resistance-welding loads is usually separated from the general plant power supply. Generally speaking the voltage disturbances produced by the resistance-welding load cannot be tolerated on other plant loads, particularly lighting. For this reason

an attempt is made to minimize these disturbances by separating the two loads as much as possible.

Installations—Company A

1. Method of Service by the Power Company

The power company provides service for all plant load, including the resistance welders, through a step-down substation consisting of two 6,000-kva three-phase transformers connected 24,000/-2,400 volts, located on the plant property as near as practicable to the load. Each transformer is radially fed by means of an underground cable from a 24,000-volt substation located about one-quarter mile from the plant. The transformer secondaries are solidly connected to the 2,400-volt bus. The 2,400-volt plant feeders are connected to the bus through oil circuit breakers and double-throw disconnecting switches, as shown in figure 1.

2. Cost to the Power Company to Serve Welder Load

No special consideration or expense was required by the power company to serve the welder load. The step-down substation was needed to supply the load at the voltage required, and the 24,000-volt supply to the substation was of ample capacity to take the kilovolt-ampere swings of the welder without producing troublesome flickers.

No other customers are fed from this step-down substation and so the power company has not been concerned by the flicker on the 2,400-volt bus. If, in the future, some new load develops in this area that could advantageously be fed from this substation, it might be necessary to set aside one substation transformer for welders and other flicker-producing load and use it also as the "throwover."

3. Plant Distribution for Welders

The welder power transformers which supply the welder bus are three 1,000-kva single-phase 2,400/480-volt 4.4 per cent impedance, connected delta-delta in a three-phase bank. They are fed from the primary room by three 250-foot lengths of 500,000-circular-mil three-conductor cables, operating in parallel. The transformers are located on the roof near the load center of the welders. The 480-volt transformer bus is made up of two one-quarter- by four-inch copper bars per phase. Solidly connected to the transformer bus are 12 three-phase feeders of three single-conductor 500,000-circular-mil cables distributed over the entire bus. These feeders are brought down from the transformer bus on the roof to the welder room in four groups of three three-phase feeders. Each group is supported in wooden cleats and taped together. In the welder room, the four groups of three feeders divide into two groups of six feeders each. One group extends about 80 feet east and the other about 160 feet west from the transformer bus. The three conductors of each three-phase feeder are taped together and supported from messenger cable strung from the building girders above the line of welders. Each welder is connected to the same phase of each of the six three-phase feeders so as to divide the load about equally among the six feeders. The different welders are connected to the three phases so as to have about an equal load division on the three phases.

4. Cost Data on the Welder Feeder

Low cost was obtained by the use of the same size copper (500,000 circular mil) throughout.

5. Welder Feeder Protection

All connections are solid from the oil circuit breakers in the primary room to the welder. The oil circuit breaker is automatic and set for time-delay trip on overload.

6. Type and Rating of Welders

The welders are all flash welders of which four are rated 750 kva and three are rated 500 kva.

7. Voltage Drop

Voltage-drop data given below are calculated values in per cent based on a single-phase load of 800 kva of welding current at 0.4 power factor, 480 volts.

1. At 24,000-volt bus in power company substation....................0.7
2. At 2,400-volt bus in plant switch house..............................2.3
3. At 480-volt transformer bus........4.7
4. At welder, including 65-foot welder bus................................5.0

The voltage drop for the above four items is accumulative and represents the total drop to each point. To find the drop in any particular part of the system, for example, the drop from the 480-volt transformer bus (item 3) to the welder over 65 feet of bus (item 4) is 5.0 per cent minus 4.7 per cent equals 0.3 per cent.

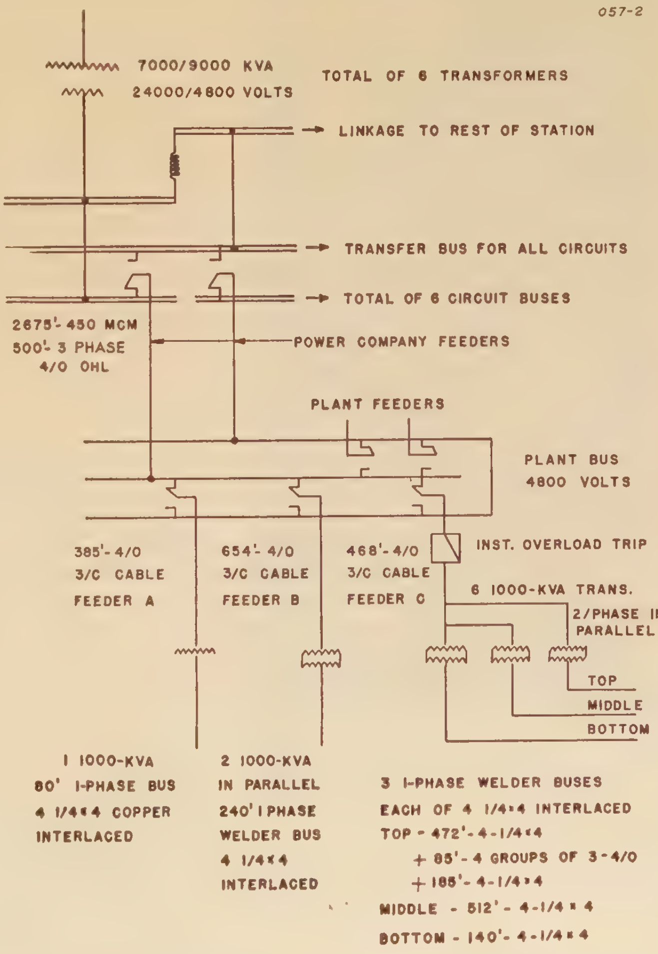

Figure 2. Schematic diagram of welder supply system—company B

8. Equivalent Thermal Loading

The heating load on the welder feeder obtained by maximum-demand heater-type ammeters was approximately 128 amperes per phase at 2,400 volts, which was 530 kva. The heating load in per cent of total connected welder kilovolt-amperes is 530/4,500 equals 11.8 per cent. At the time these readings were taken, it was known that only 3,500 kva of welders were actually operating. The heating load in per cent of operating-welder kilovolt-amperes was 530/3,500 equals 15.2 per cent.

Company B Installation

1. Method of Service by the Power Company

This plant is fed by two 4,800-volt power lines out of a 24,000/4,800-volt step-down substation as shown in figure 2. The step-down substation consists of six 7,000/9,000-kva 24,000/4,800-volt three-phase radially fed transformers, serving six 4,800-volt circuit busses. Each transformer is linked to the rest of the substation through reactors and a linkage bus. The circuit busses occupy the lower position of a double bus arrangement with a transfer bus above. The transfer bus is a continuous section energized from the linkage bus.

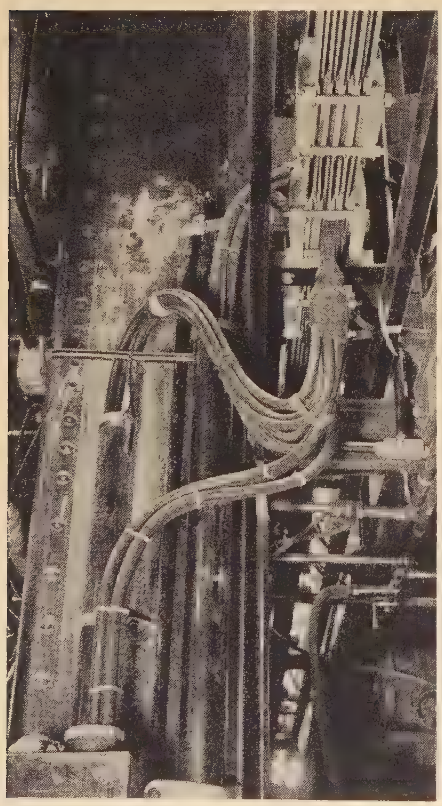

Figure 3. The interlaced welder bus used by company B, showing construction and method of making taps for individual welders

Bus consists of four one-quarter by four-inch copper bars on one-inch centers, insulated by means of five one-eighth by six-inch Micarta strips

The plant primary room bus is also a double-bus arrangement with a power line feeding each bus. The welder feeders are operated on the "throwover" bus and general plant load on the other bus.

2. Cost to the Power Company to Serve Welder Load

Originally the power line supplying the welder load was connected to a circuit bus at the substation with only power load. On such a bus the flicker limit is three volts (at lamp voltage) which would permit 1,500-kva load swings. The plant later increased the size and number of welders until load swings exceeded 2,000 kva and caused voltage flickers of four to five volts, and complaints from other customers on this bus.

There were sufficient spare positions at the substation so that it was possible by rearranging and transferring lines to set aside one circuit bus for this welder load. At present this circuit bus carries only the load of this one power line, but the transformer is still connected to the other busses through the linkage. If the load in this substation area increases and the spare positions on this bus are needed for new load, it may be that enough of this new load will be flicker load to provide satisfactory loading for the transformer. This has happened at other substations where a bus has been set aside for special load. Another alternative might be to use the spare positions on this bus as "throwover" lines to other customers. It is not felt in this case that the power company has been put to any appreciable added expense to serve this welder load.

3. Plant Distribution for Welders

The welding transformers are located at three different parts of the plant and are supplied by three 4,800-volt feeders from the primary room. Feeders *A* and *B* (figure 2) serve general plant load as well as welders, while feeder *C* serves welder load only. The welders are tapped to single-phase 480-volt busses made up of four one-quarter by four-inch copper bars with the going and return bars interlaced on one-inch centers with a Micarta spacer between each bar and on each side of the entire assembly as shown in figure 3. The bus is of open construction supported from the building pillars shown in figure 4. To reduce the chance of short circuits from foreign material falling across the bars, the Micarta spacers extend about one inch above the bars. Data on each of the feeders are given below:

Feeder A

1. 350 feet of three-conductor 4/0 cable from primary house to transformer

2. Supply transformer—one 1,000 kva, single phase, 4,800/480 volt, 4.6 per cent impedance

3. Feeder bus—80 feet four one-quarter by four-inch copper bars interlaced

Feeder B

1. 654 feet of three-conductor 4/0 cable from primary house to transformers

2. Supply transformers—two 1,000 kva, single phase, 4,800/480 volts, 4.6 per cent impedance, two in parallel

3. Feeder bus—240 feet four one-quarter by four-inch copper bars interlaced

Feeder C

1. 468 feet of three-conductor 4/0 cable from primary house to transformers

2. Supply transformers—six 1,000 kva, single phase, 4,800/480 volt, 4.6 per cent impedance (two transformers in parallel on each phase)

3. Feeder bus:

Top bus—472 feet of four one-quarter by four-inch copper bars interlaced plus 85 feet of four interlaced groups of three 4/0 cables, each on about four-inch centers to another bay and there 185 feet of four one-quarter by four-inch copper bars interlaced

Center bus—512 feet of four one-quarter by four-inch copper bars interlaced

Bottom bus—140 feet of four one-quarter by four-inch copper bars interlaced

4. Cost Data on Welder Feeder

The welder bus cost was $10.50 per foot installed.

5. Welder Feeder Protection

There is no protection provided on feeders *A* and *B*. The oil circuit breakers in the primary room are nonautomatic. The oil circuit breaker of feeder *C* is automatic and set for instantaneous tripping on overload. The power company's incoming line is also provided with an automatic instantaneous-tripping oil circuit breaker, so it is doubtful if a worthwhile degree of selectivity is obtained between the plant feeder *C* breaker and the power company's breaker.

6. Type and Rating of Welders

The type, number, and rating of the welders on each bus are given below:

Feeder A

Projection, flash, and seam	6
Total connected load (kva)	2,000
Largest single unit (kva)	500

Figure 4. Two separate interlaced welder busses used by company B, showing method of support

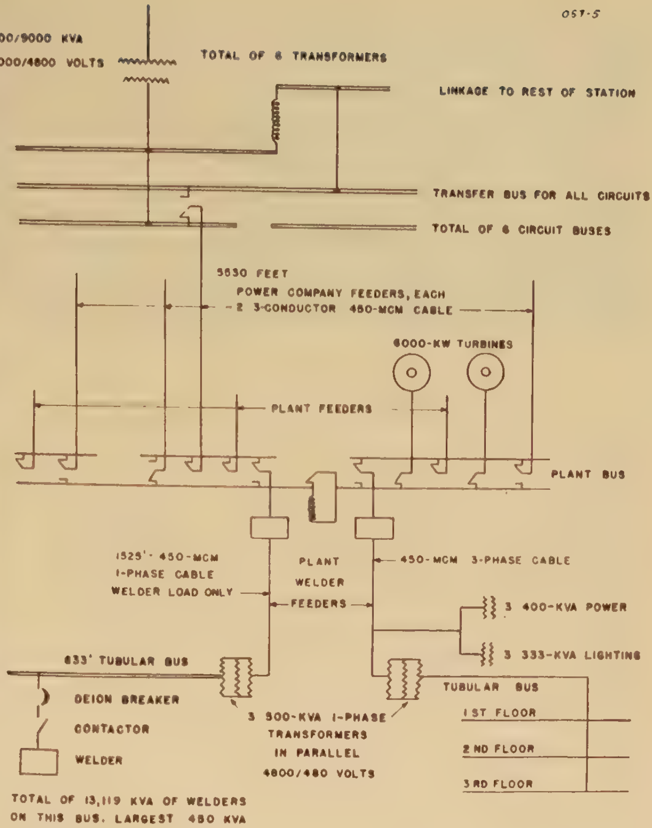

Figure 5. Schematic diagram of welder supply system—company C

Feeder B

Projection and butt	9
Total connected load (kva)	1,700
Largest single unit (kva)	750

Feeder C

Top Bus

Projection and flash	11
Total connected load (kva)	1,960
Largest single unit (kva)	600

Center Bus

Projection and flash	11
Total connected load (kva)	2,750
Largest single unit (kva)	600

Bottom Bus

Projection and flash	3
Total connected load (kva)	1,250
Largest single unit (kva)	600

Test data have been obtained on two of the largest welders used.

1. 600-kva projection welder; maximum swings, 960 kva, 2,110 amperes, 450 volts at 0.347 power factor at welder (1,000 kva at substation)

2. 750-kva welder; maximum swings, 1,760 kva, 4,300 amperes, 418 volts at 0.299 power factor at welder (2,100 kva at substation)

7. Voltage Drop Caused by Welder Load

The voltage drop in per cent at various points has been calculated and is based on a load of 2,100 kva at 480 volts, 0.4 power factor.

1. At substation, 4,800-volt bus	3.5
2. At plant primary-room 4,800-volt bus	6.4
3. At welding-transformer primary	7.1
4. At welding-transformer secondary (two 1,000 kva in parallel)	11.8
5. At welder over 100 feet of four one-quarter by four-inch bus	13.0

The voltage drop for the above five items is accumulative and represents the total drop to each point. To find the drop in any particular part of the system, for example, the drop from the welder transformer secondary (item 4) to the welder over 100 feet of bus (item 5) is 13.0 per cent minus 11.8 per cent equals 1.2 per cent.

8. Equivalent Thermal Loading

There are no available data on thermal loading on the individual feeders. For the total connected load of 9,660 kva, the average kilovolt-amperes or thermal load is approximately 900 kva, or slightly less than ten per cent.

Company C Installation

1. Power Company Method of Service

The step-down substation from which this plant is fed consists of six radially fed three-phase transformers of 7,000/9,000 kva, 24,000/4,800 volts, feeding six 4,800-volt circuit busses as shown in figure 5. The transformers are linked by reactors on the 4,800-volt side. The circuit busses and transfer bus form a double bus arrangement, with the transfer bus tied to the linkage bus. The short-circuit kilovolt-amperes on each 4,800-volt circuit bus is 147,000 kva.

Each power line to the plant consists of two cables of 450,000 circular mils and supplies a separate bus at the plant primary house. In addition to the power-company supply, there are two 6,000-kw turbines at the plant which operate in parallel with one power-company line.

2. Power Company Cost to Serve Welders

The substation bus supplying this plant can stand 1,500-kva swings without exceeding the flicker limit of three volts on the substation bus. This limit has never been exceeded, and so there has been no additional expense to serve the welder load.

3. The Welder Feeders

There are two welder feeders, but since their construction is nearly identical detailed description will be given for only one of the feeders.

This feeder consists of 1,525 feet of 450,000-circular-mil single-phase cable from the primary house to three 500-kva 4,800/480-volt transformers connected in parallel. The 480-volt welder bus is connected solidly to the transformer

Figure 6. The concentric tubular bus used by company C, construction and method of support

The bus is made up of bare four-inch standard copper tubing over a three-inch extra-heavy tube with a Micarta-tube separator. Taps for the individual welders are provided every six feet

Figure 7. Showing welder bus and controls used by company C

The controls are mounted on racks alongside the bus, and consist of De-ion circuit breaker, welding contactor, and timer for each welder

secondary and extends about 633 feet through the factory and serves a large number of production-type welders. The bus is copper tubing made up of a four-inch standard tube over a three-inch extra heavy tube with a Micarta tube separator. The outer tube is bare, solidly grounded, and supported by the building girders (figure 6). There is a tap provided on the bus every six feet. The De-ion breaker contactor and timer for each welder are located on a rack by the welder bus (figure 7). The lead into each welder is made of special cable with the control wiring laid in the main cable. This cable required no conduit.

4. Welder Bus Cost

The cost of the tubular bus, made up of four-inch standard tubing over three-inch extra-heavy tubing in 12-foot sections with taps every six feet is about $9 per foot. Installation cost is extra and will depend somewhat upon local conditions.

This company uses two-inch standard tubing over one and one-quarter-inch extra-heavy tubing on the branches of the second welder bus, but no figures are available on its cost.

5. Bus or Feeder Protection

Faults on the welder bus or the 4,800-volt supply are cleared by the oil circuit breaker at the primary house. The breaker is tripped after a time delay by an induction-type overcurrent relay and is selective with the main supply breaker from the power company. Each welder tap has a De-ion type air breaker which is a two-pole breaker with the poles in parallel. This gives it a rating of 190 amperes and an interrupting rating of 10,000 amperes. The breaker is set for instantaneous tripping at about eight to ten times the breaker rating. The thermal trips were found to be unsatisfactory and have been disconnected.

6. Type and Rating of Welders Served

This feeder serves a total of 13,119 kva of welders of various types and ratings. The list given in table II is fairly representative of the types and sizes served.

7. Equivalent Thermal Loading

The following readings were obtained during normal production on the feeder which supplies welders only:

Connected kva	13,119
Normal peak kva	860
Average load kva	610
Average load kw	304
Average power factor	304/610 = 49.8 per cent
Average kva/-connected kva	610/13,119 = 4.8 per cent

8. Voltage Drop Caused by Welder Load

Voltage drops in per cent are:

1. At the substation bus, 4,800 volt . . 2.5
2. At the plant primary house, 4,800 volt . . . 3.8
3. At the welder transformer primary, 4,800 volt . . . 4.5
4. At the welder transformer secondary, 480 volt . . . 8.7
5. At the welder over 633 feet of bus . . 11.3

The above figures are calculated for 1,500-kva 0.4-power-factor, 480-volt welder load supplied by one power-company line and do not take into account any assistance obtained from the plant generators.

The voltage drop for the above five items is accumulative and represents the total drop to each point. To find the drop in any particular part of the system, for example, the drop from the welder transformer secondary (item 4) to the welder over 633 feet of bus (item 5) is 11.3 per cent minus 8.7 per cent equals 2.6 per cent.

Company D Installation

There are at present 269 resistance welders installed in this plant, with the following name-plate ratings:

Number of Welders	Rating (Kva)
51	Under 5
70	5 to 25
25	30 to 50
60	60 to 100
26	125 to 175
26	200 to 300
6	350 to 400
1	500
2	600
1	750
1 five head	1,500

Electronic control is used wherever accurate timing and synchronous switching is required. In installations requiring less accurate control, ignitron contactors are now being used in place of the former standard magnetic contactor in order to cut down service costs.

Practically all the welders are at present protected by enclosed fused switches. Where control equipment and switch are located at a distance from the welder, it is customary also to include a line contactor operated from a tumbler switch at the welder. In future, however, enclosed air circuit breakers will be used with all but the smaller units. These breakers will be either manually or electrically operated, depending on their location in respect to the welders, and will have instantaneous overload trips, in some cases with an additional undervoltage trip coil operated by a thermal overload relay incorporated in the welder control.

From the standpoint of power supply, these welders may be divided into three classes, as follows:

Class I

This includes resistance welders of all types, both with and without electronic control, which are installed as separate units and obtain power from the regular 575-volt three-phase 60-cycle shop lines. With the exception of a few spot or projection welders, the name plates of which may be as high as 350 kva, these welders are not rated over 150 kva or, in the case of multiple-head machines, the individual welding heads do not exceed this limit. About 94 per cent of the resistance welders are in this class.

Before connecting a welder to a shop line, consideration is given to the effect

Table II. Type and Rating of Welders—Company C

Type	Kilovolt-Ampere Rating	Normal Current	Maximum Current	Rated Current at Rated Volts
Gun	50	150	550*	114
Gun	75	300	500	170
Hydromatics	100	300	550*	228
Hydromatics	150	300	800*	340
Spot and projection	450	5,000	6,000*	1,000
Spot and projection	50	300	650*	114

* Estimates based on test readings. This company generally figures five to eight times rated kilovolt-amperes for momentary load.

of voltage drop, caused by the actual power demand during weld, on other load supplied by that line. Inasmuch as most of the lighting load is on d-c or separate a-c lighting feeders, it is possible to permit fairly large momentary voltage variations on the a-c shop feeders without undesirable results. Figure 8 shows a typical section of the 60-cycle distribution. This distribution system is designed to supply shop load, and neither its cost nor design has been directly affected by welders of this class.

The central substation *A* from which the primary feeders of this system radiate has a capacity of 30,000 kva with a calculated bus short-circuit value of 500,000 kva. Primary power is distributed at 13.8 kv three phase, grounded neutral, over 17 feeders, most of which are rated 4,800 kva and consist of three-conductor 4/0 15-kv cable. Each feeder has a five per cent current-limiting reactor which limits feeder short circuits to approximately 100,000 kva. Relaying of feeder oil circuit breakers is for short-circuit protection only. These feeders serve 24 substations each of which has an emergency tie to at least one other than its normal feeder.

Substations vary from 1,800 to 3,500 kva in transformer capacity, the more recent transformer units being 1,500 kva instead of the 600 kva shown in figure 8. Although the 800-ampere 600-volt manually operated oil circuit breaker has been standard for 575-volt feeder protection, air circuit breakers will be used in any new substation construction. This also applies to shop entrance panels.

Secondary feeders are 575 volt, three phase ungrounded, and consist usually of one three-conductor 500,000-circular-mil cable nominally rated 400 kva. If more capacity is needed a similar cable is added in parallel or a separate feeder is established. Length of feeder between substation and building may be up to 1,000 feet. Inside building feeders usually are of open construction extending the length of the building and may be of the particular line capacity and demand involved.

Class II

This covers group installations of welders where the voltage disturbances set up by the operation of one or more of the welders, if from the shop 575-volt lines, would interfere with the operation of other welders of the same group. In some cases such installations can be supplied from the nearest substation through a special low-impedance line, but in two installations the following methods have been used.

The first group consists of 14 seam welders and one projection welder four of them having two welding transformers each (figure 8). Name-plate rating of the group is 2,524 kva, 550 volts. The 19 electronic controls required, together with their protective equipment, are mounted together on a centrally located overhead platform. Directly below the

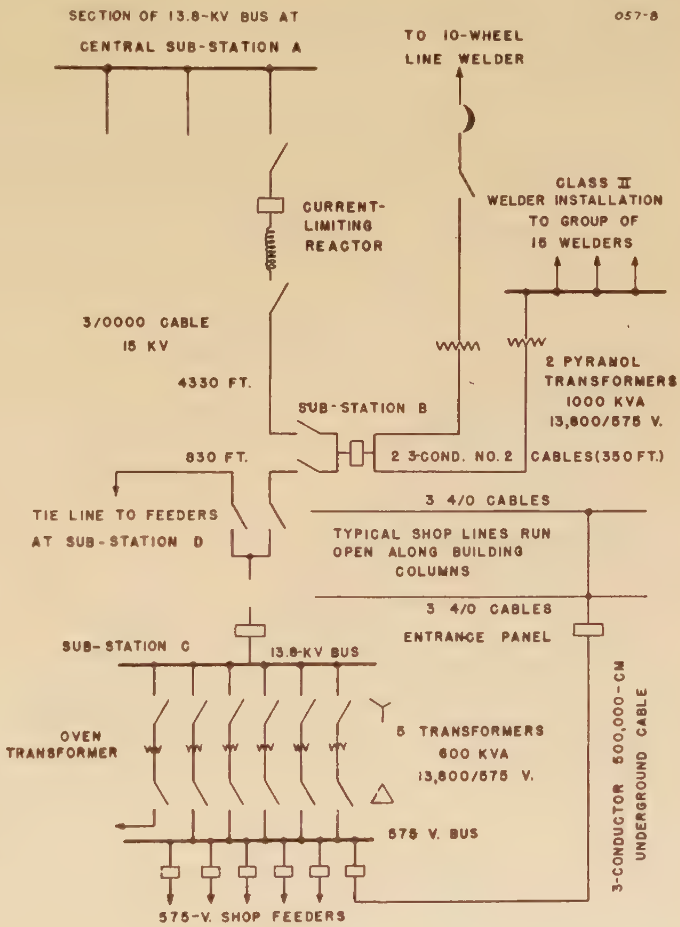

Figure 8. Schematic diagram of typical welder supply system—company D

anywhere from number 0000 to 1,000,000 circular mils in size. It is obvious that the larger welders in this class cannot be fed from the more remote sections of the shop 575-volt lines, and as mentioned above, each case must be considered in the light

platform is installed a Pyranol-filled transformer rated 1,000 kva, 13,800/575 volts. The low-voltage side of this transformer is connected to a short bus directly underneath the platform floor, from which connection is made through

two-pole fused enclosed switches to each separate welder and control. Each welder control is also equipped with a two-pole contactor, operated from a tumbler switch at the welder, which opens the power circuit to the welder without removing control voltage from its control panel. With all welders operating under normal production, the actual load, as measured with indicating instruments, is 1,116 kva, three phase, with a maximum unbalance between phases of $12^1/_2$ per cent, and an average 0.45 power factor. (Note that these are short-throat welders.) Bus voltage averages 549 volts with a maximum variation plus and minus of $3^1/_2$ per cent. It is probable that the average kva load over a period of several hours is slightly below the measured amount which may explain why there is no trouble with overheating the 1,000-kva power transformer.

A second installation directly adjoining the above consists of one seam welder equipped with five welding heads each with a 300-kva name-plate rating. Control consists of electronic panels mounted on an extension of the above-mentioned platform. Power is obtained from a second 1,000-kva three-phase Pyranol-transformer similar to the one mentioned above and located directly below the platform. The low-voltage side of this transformer is connected through a manually operated disconnecting switch and a 1,200-ampere three-pole inverse-time-limit electrically operated enclosed air circuit breaker directly to the five welding circuits and controls. Excitation for the controls is fed through an enclosed fused switch tapped into the line ahead of this breaker so that the breaker, which is operated from a push-button station at the welder, may be opened without breaking the control excitation. Under normal operation this welder demands approximately 1,500 kva with a 66 per cent duty cycle (two cycles on, one off) and draws, as measured with indicating instruments, 1,006 kva, three phase, with a maximum unbalance between phases of 22 per cent and an average 0.50 power factor. Supply voltage averages 525 volts with the welder in operation, and 550 volts at no load, with a plus and minus variation at either point of two per cent.

The primary power supply to these two installations is taken from one of the regular shop 13.8-kv feeders *A* indicated in figure 8.

The control panel for the 13.8-kv oil circuit breaker is located on the welder control platform. Connection to the high side of each transformer is through pothead-type terminals which in turn are protected by an additional steel enclosure.

Class III

This includes large electronically controlled projection or spot welders where, although the equivalent continuous load is not great, the line-current demand at the time of making the weld is so high that it is inadvisable to supply it from the regular power transformers of one of the shop substations. In general, this applies to welders having a demand in excess of 2,000 amperes root mean square, 550 volts, during weld.

There are at present two installations that illustrate this classification. The first is a projection welder rated 550 volts, 500 kva (50 per cent duty cycle). Power for this welder is brought through a two-conductor 750,000-circular-mil concentric cable 500 feet long, from a special transformer. This transformer is rated 1,260 kva, 13,800/287.5-575-1,150 volts, and is designed to supply 15,000 amperes (peak) when connected for 575 volts. Maximum current obtainable at the welder is 2,200 amperes root mean square during weld with about 70 volts drop in the line.

The second welder in this class is a spot welder with name-plate rating of 550 volts, 750 kva, equipped with electronic control arranged for interrupted-operation welding. Power is obtained from a special transformer rated 840 kva, 13,800/635 volts and designed to give an impedance drop of less than 15 per cent when loaded at 6,000 amperes, 0.60 power factor. This transformer is located outside the building about ten feet from the welder and is fed from the 13.8-kv bus of the nearest shop substation through two lines of a three-conductor 15-kv underground cable approximately 210 feet long. This substation is in turn fed by a 13.8-kv feeder 3,800 feet in length, similar to the one shown in figure 8. Protection for both the welder and the power transformer is by an oil circuit breaker located in the shop substation and controlled from a panel adjacent to the welder. Both thermal and instantaneous overload relays are provided. Also the midpoint of the 635-volt winding of the power transformer is grounded through a current transformer which operates an instantaneous relay of low current setting to trip the circuit breaker in the event of a ground in either the welder transformer or control. The low-voltage side

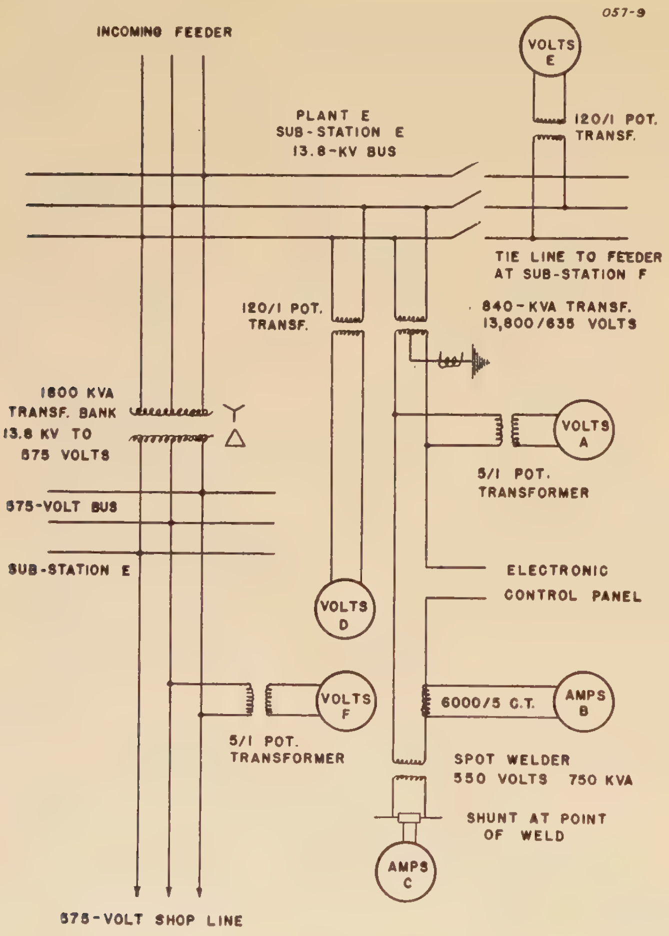

Figure 9. Location of voltage and current readings taken during test of power-supply system with 750-kva spot welder in operation—company D

of the power transformer is directly connected to the control and welder through a two-pole manually operated disconnecting switch.

Recently tests were made to show the effect of the operation of this welder on various parts of the power system. The welder was operated at maximum capacity with a duty cycle of 4 cycles on and 54 off. All readings were taken simultaneously on an oscillograph with the following results. Figure 9 indicates the points at which these readings were taken.

A. Voltage of 603-volt supply to welder dropped 21.9 per cent (note that drop as read on indicating voltmeter was only 4.5 per cent).

B. Current of 603-volt supply to welder was 4,800 amperes (root mean square during weld).

C. Current in weld was 90,600 amperes (root mean square during weld).

D. Voltage of 13.8-kv bus in substation *E* at point of feed to welder power transformer dropped 9.7 per cent.

E. Voltage of the 13.8-kv tie line to substation *F* dropped 4.4 per cent. This indicates the drop on the central substation bus as this tie line is energized from a 13.8-kv feeder different from the one supplying the welder. Note that the capacity of the supply to the central substation bus was one-half normal at the time these tests were made.

F. Voltage of the 575-volt shop lines in plant *E* supplied through wye-delta-connected transformer bank substation *E* dropped 6.7 per cent.

All readings but the last were definitely taken from the same phase. It should be noted that the general plant voltage drop of 4.4 per cent (in one phase) observed at *E* is reduced one-half when the central substation bus is operating with full-capacity supply, and is probably further reduced by the time it reaches the 575-volt distribution system by the balancing effect of synchronous- and induction-motor shop load.

Company E Installation

In this plant like in many others where acquisition of new equipment and general expansion have been gradual, the majority of the welding equipment is widely scattered all over the plant. Furthermore, because of the nature of the plant's business, drastic changes in the location of a large portion of the welding equipment available are quite frequent. When they occur, certain general shifts in power loads and temporary feeds are sometimes made which result in different power-supply conditions.

For these reasons to present a general picture of the power feed of all welding equipment used would be both difficult and inconclusive. Accordingly this report is limited to a description of power supply of one group of welders which, because of the time and permanency of their installation, can be treated as an integral unit.

General Description of Equipment

The resistance-welding equipment comprising this group consists entirely of spot and seam welders. All but two are of the pedestal stationary type. One is a fully portable welding gun and one a semiportable type with provision for 30-foot travel. All stationary machines are located within 50 feet of the distribution board.

The kilovolt-ampere capacities of the equipment are shown in figure 10. It will be noted that several of the machines have full-load capacities of such magnitude that were they to form part of the normal production load unsatisfactory voltage regulation would result with the power supply available. However, the maximum production requirements of these machines are considerably lower, as shown on the "normal maximum" line, and rather than increase the power-supply installation mechanical provisions are made preventing the setting of these machines at a tap higher than the normal maximum for all work except experimental which is conducted by plant engineers only when this group is inoperative, and with one machine at a time.

Load Conditions

The total maximum load is 1,375 kva. This load, however, corresponds to operation with short-circuited secondaries. The actual working loads of these machines run 5 to 15 per cent less, depending on the machine and the material used. Assuming an average of 10 per cent, the actual maximum load becomes 1,237.5 kva. Application of this load to the 460-volt bus results in a net drop of 13.6 per cent on this bus which would be excessive from the welding point of view. In addition it produces a 5 per cent drop on the 2,300-volt bus which is also considered undesirable.

However, the application of maximum load presupposes two facts: (1) that every machine is operated at its maximum setting; (2) that every machine should fire at the same time. As the machines are operated most of the time at setups averaging 50 per cent capacity, and as the combined duty and welding cycle (time of flow of current to total operating time) is between 5 per cent and 25 per cent, the probable maximum load is considerably smaller.

Prolonged and extensive oscillographic studies of the group failed to reveal load peaks higher than 500 kva with a highest daily average around 250 kva.

No attempt has been made to measure the kilowatt or kilowatt-hour loads as no evidence of heating of transformers, equipment, or feeders has ever been observed.

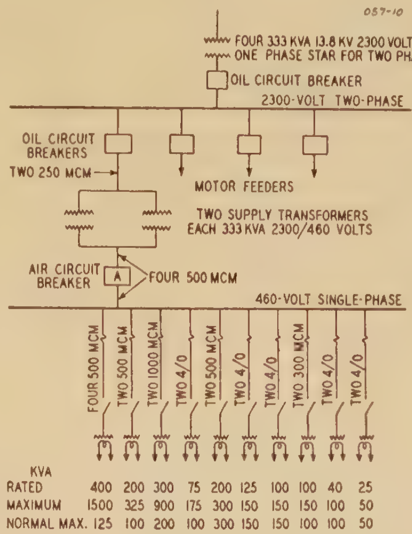

Figure 10. Schematic diagram of welder supply system—company E

Power Supply

The power is supplied by two 333-kva 2,300/460-volt single-phase 3.56 per cent impedance oil-immersed self-cooled transformers connected in parallel. The transformers are installed on an outdoor platform adjacent to the floor housing the welding equipment. The 460-volt bus and distribution are thus not over ten feet from the transformer bank.

The transformer bank is fed from a 2,300-volt bus which, in addition to the welding load, also feeds a miscellaneous motor load averaging about 300 kva, two phase, with a normal maximum 15-minute demand of around 650 kva, two phase.

The 2,300-volt bus is fed by a 930-kva, two-phase transformer bank (belonging to the power company) consisting of four 333-kva 13,800/2,300-volt single-phase oil-immersed self-cooled transformers, star connected.

Distribution System

The 2,300/460-volt transformer bank is fed from the 2,300-volt bus by two 250,000-circular-mil stranded copper cables through an automatic oil circuit

breaker equipped with instantaneous overload trip normally set at 500 amperes. The circuit breaker thus, besides providing short-circuit protection, provides against dangerously high overloads which would result in excessive voltage drop.

The secondary side of the 2,300/460-volt bank is connected by four 500,000-circular-mil stranded copper cables through an air circuit breaker to a fused distribution board. The individual machines are connected to the distribution board by feeders whose size is based on their length in such fashion that their voltage drop at the normal maximum load shall not exceed 0.25 per cent.

The 460-volt bus is provided with a recording voltmeter and an audible undervoltage alarm signal set to operate at a $7^1/_2$ per cent drop below the normal open-circuit voltage.

Conclusion

The extensive voltage-regulation studies, extending over a period of several years, appear to indicate that the normal voltage fluctuation on the 460-volt bus is plus or minus three per cent of the average operating voltage. Under exceptional operating conditions a drop of minus four per cent has been observed. At the same time the voltage fluctuation of the 2,300-volt bus during normal operating conditions has been plus or minus two per cent of the average operating voltage.

These voltage conditions appear to be entirely satisfactory both from the plant operating and welding standpoints. For this reason the company has discontinued the use of an automatic instantaneous-operation-type voltage regulator which was originally part of this installation. The use of the voltage regulator, although it proved to be entirely practical, did not appear to be justifiable in this case as it presented certain problems and the further improvement in the voltage regulation it offered did not appear to be essential.

Company F Installation

1. Method of Service by Power Company

The power company supplies all of the load at the plant through two step-down transformer banks each rated 1,500 kva. One bank supplies all the small loads from a 120/208-volt radial system and the second bank supplies all the large loads and welders in the plant at 240 volts. The transformer banks are supplied from a 13,200-volt circuit, which is fed from two large substation busses. The entire load is metered on the primary side of the transformers and the customer owns the transformers.

2. Cost to Power Company to Serve Welder Load

No special equipment or expense was required by the power company to supply the welder loads. Voltage dip was not great enough to cause objectionable light flicker.

3. Plant Distribution for Welders

The transformer bank supplying the welders consists of three 500-kva transformers connected delta-delta of 4.4 per cent reactance and 1.7 per cent resistance. The welders are in two groups at two widely separated locations.

The first group, of which the largest welder is rated 125 kva, is supplied over a three-phase line consisting of three sets of three 800,000-circular-mil copper conductors in parallel. Other welders in the group are taken from a three-phase bus about 100 feet long made up of two one-quarter by four-inch copper conductors per phase, also supplied from the 800,000-circular-mil conductors.

The second group, of which the largest welder is 400 kva, is supplied from about 50 feet of three-phase bus made up of four one-quarter by four-inch copper bars per phase, with a spacing of one-half inch between bars. The center lines of the phases are spaced about six inches apart.

Welder-Feeder Protection

The bus to the second group, which includes the largest welders, is connected directly to the secondaries of the power transformer. The circuit to the other group is supplied through a low-voltage air circuit breaker.

Type and Rating of Welders

The largest welders in both groups are spot welders. The first group includes 21 welders having a combined rating of 1,300 kva, of which the largest is 125 kva. The second group includes 5 welders having a total rating of 1,100 kva of which the largest is 400 kva.

Voltage-Drop Data

The following calculated voltage drops at various points on the distribution system apply to 0.4-power-factor loads, which oscillograph records show to be closely approximated:

	Per Cent	
	Location 1, 800-Kva Load	Location 2, 150-Kva Load
On 13.2-kv line at the plant	1.5	0.3
On 240-volt bus	5.3	1.0
On 240-volt circuit at welder	8.0	2.0

Equivalent Thermal Heating

The timing on all of the spot welders is between 15 and 20 cycles. The time between welds is about three seconds on the larger welder and one second on the smaller group. The equivalent kilovolt-amperes on a heating basis is about 150 kva for the larger group and was about 275 kva for the smaller group.

Transactions

Preprint of Papers and Discussions Comprising Pages 321–368 of the 1940 Volume

Upper-Air Weather Soundings by Radio

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Synopsis: A radio system for upper-air weather soundings with small unmanned balloons is described. The balloon instrument comprises elements for measuring pressure, temperature, and humidity, and a miniature radio transmitter; the latter converts the response of the measuring instruments into characteristic signals modulating the emitted radio wave and sends this wave to a ground station where the signals are measured and recorded. Details of the system are given and a discussion is given of the accuracy of the upper-air observations obtained and of the tolerances permissible for component elements of the system.

I. Introduction

A RECENT significant advance in weather forecasting is based on the routine collection of upper-air data to heights of up to 25 kilometers by means of radio soundings. This paper describes a method of radio sounding now in widespread use and presents a discussion of the accuracy of the observations. This method has recently supplanted the use of airplanes carrying calibrated recording instruments for securing upper-air data.

The radio-sonde system employs an instrument carried aloft on a small unmanned balloon, and ground-station receiving and recording equipment. The balloon instrument, called a radio sonde, comprises elements for the measurement of barometric pressure, air temperature, and humidity; a radio transmitter and power supply; and means for impressing on the radio transmitter modulating frequencies which have predetermined relationships to the values of the factors measured. At the ground station, the frequencies of the received signals are measured and recorded automatically, producing a chart of temperature and humidity plotted against pressure.

Figure 1 (at the left) shows a radio sonde just as the sounding has begun. The balloon is of latex rubber and is inflated with helium or hydrogen gas to give a lift of about one kilogram in excess of the over-all weight of the sounding equipment. An ascensional rate of approximately 200 meters per minute is obtained. The diameter of the balloon is about 5 feet at surface pressure and reaches a value of the order of 15 feet before bursting; the corresponding maximum altitude ranges from 20 to 25 kilometers. A small silk parachute between the balloon and the instrument operates when the balloon bursts, bringing the instrument back to earth at a safe rate of descent. See figure 1 (at the right). The wind may carry the balloon up to 200 miles from the point of release before the equipment returns to the earth; nevertheless, more than a third of the radio sondes released are recovered and are used over again.

The potential value of our method of radio sounding was determined in experimental use by the Weather Bureau, Navy Department, and Coast Guard at 12 stations during 1938–39. The service has since been expanded to include some 30 land and 5 shipboard stations; more than 1,000 radio sondes being used monthly.

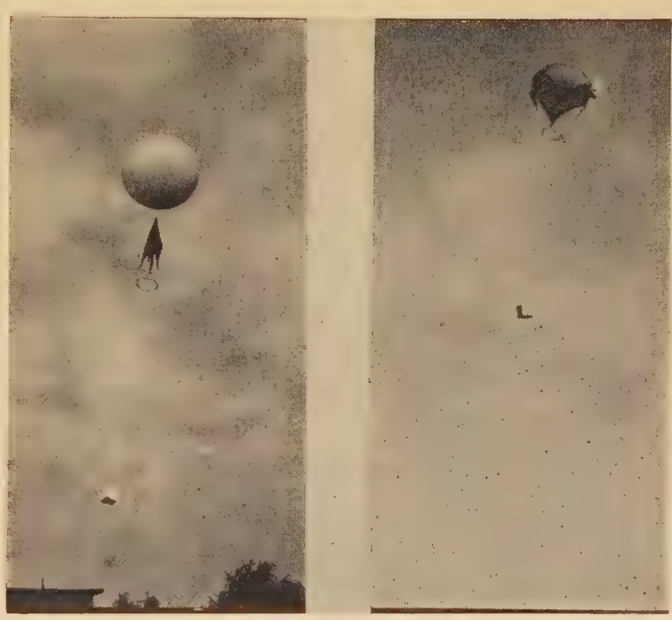

Figure 1. Radio sounding equipment during ascent and descent

This paper deals with an improved form of radio sonde using this method which incorporates a new device for measuring relative humidity; the improved instrument has been introduced at nine stations and its use at one more is contemplated in the near future.

A bibliography on radio methods for upper-air soundings was given in an earlier paper.[1] The method herein described was developed under the sponsorship of the Aerological Service of the United States Navy Department with the object of providing a new approach toward meeting the rigid operating requirements faced. In the latter stages of the development, considerable co-operation was had with Julien P. Friez & Sons, Baltimore, Md.

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1. For all numbered references, see list at end of paper.

The instrument requirements are rather severe. Measurements of pressure, temperature, and humidity are desired to heights of up to 25 kilometers. In such excursions, the range of pressures encountered may be from 1,070 millibars at the surface to 25 millibars at the top, the range of temperatures from +40 to −90 degrees centigrade, and the range of humidities from 0 to 100 per cent relative humidity. The required accuracies of measurement are ±5 millibars throughout the range of pressures, ±0.75 degree centigrade at temperatures above −50 degrees, and ±5 per cent relative humidity at temperatures above −20 degrees.

Superposed on the instrument requirements are practical requirements which increased materially the difficulty of the problem. Considerations of economy dictate that the unit cost of the radio sonde must not exceed the amount hitherto expended for an airplane sounding ($25 to $30) despite the facts that airplane soundings were generally limited to heights below 6 kilometers and that their regularity of operation was frequently interrupted by adverse weather conditions. The weight of the instrument must be kept sufficiently low (of the order of one kilogram) to allow its being carried to the desired height by a balloon of the dimensions given. However, a rugged construction is essential since the instrument must be capable of shipment by ordinary transportation to considerable distances and of storage for several months under field conditions without upsetting the original calibrations. Ease of handling by field personnel and minimum time requirements for making the sounding and for evaluating the observations are additional conditions.

From these considerations, it will be apparent that the practicability of a radio-sonde design depends not only on its potential accuracy of measurement but also upon the ruggedness of the component elements required and upon the possibility of their manufacture by mass-production methods. The equipment to be described complies with the requirements outlined largely because of the special arrangement devised for carrying

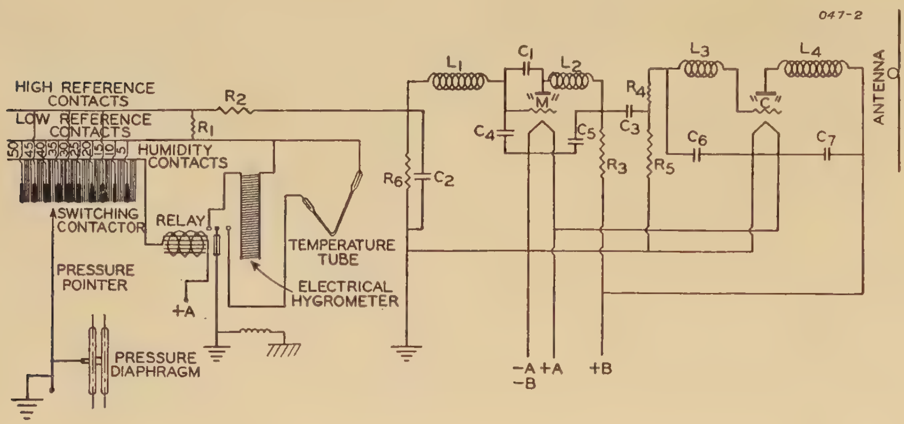


Figure 2. Electrical circuit arrangement of the radio sonde

R_1, R_4—1,000 ohms
R_2—40,000 ohms
R_3—25,000 ohms
R_5—5,000 ohms
R_6—1,000,000 ohms
C_1, C_4, C_7—0.00025 microfarad
C_2—0.07 microfarad
C_3—0.05 microfarad
C_5—0.01 microfarad
C_6—0.0001 microfarad
M—Modulating oscillator
C—Carrier oscillator

out the measurements and for translating them into signals which may be evaluated at the ground station.

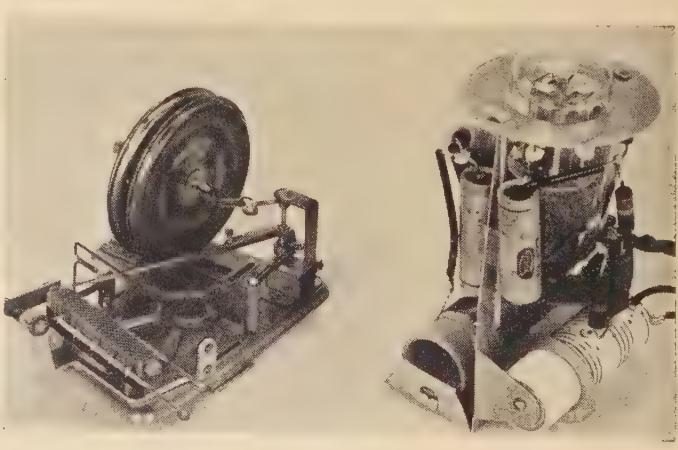
II. Technical Features of the Radio Sonde

The principles underlying the operation of the radio sonde will be understood from a study of the electrical circuit diagram shown in figure 2. As already stated, the radio sonde consists of a radio transmitter and elements for measuring pressure, temperature, and humidity. A photograph of the radio transmitter is shown at *b* in figure 3, while the pressure-measuring unit is shown at *a*. Figure 4*a* shows the temperature element and figure 4*b* the humidity element (comprising three interconnected units). The temperature and humidity elements are fastened to opposite sides of a mounting plate which fits into a ventilated compartment of the radio-sonde container. As will be shown, these elements constitute electrical resistors which vary respectively in accordance with the temperature and relative humidity of the air to which they are exposed.

1. The Radio-Sonde Transmitter

Referring to figure 2, the transmitter employs a conventional receiving-type vacuum tube having two sets of triode elements in a single glass envelope. One of the triodes is connected in a carrier oscillator circuit, operating at a frequency of 65 megacycles per second and feeding a half-wave doublet transmitting antenna. The second triode is used in an auxiliary oscillatory circuit, oscillating at about one megacycle per second and having in its grid circuit a resistance-capacitance network which operates to interrupt or "block" the oscillator at a rate inversely proportional to the time constant of this network. The capacitance is of fixed value but the resistance varies so that the "blocking" frequency ranges from 10 to 200 cycles per second. This frequency is made to modulate the carrier oscillator, resulting in an emitted carrier wave having a variable audio-frequency modulation.

The one-megacycle oscillations of the modulating oscillator (controlled by the coils L_1 and L_2 and by the capacitors C_1



(*a*) (*b*)

Figure 3. The radio-sonde transmitter and pressure-switching unit

and C_4) are used only for triggering purposes. During the oscillating condition, the grid swings positively each half-cycle and a current flows through the resistance-capacitance network formed by the capacitor C_2 in parallel with the series circuit comprising R_2, R_1, and either the temperature or the humidity resistor. (The shunt resistor R_6 sets an upper limit to the value which may be attained by the resistance in parallel with C_2.) The voltage developed across this network is applied as a negative biasing voltage on the grid. The magnitude of this biasing voltage is a function of the charging rate of the capacitor C_2 through the tube grid-filament resistance and of the amplitude of oscillation; it builds up within about 0.5 millisecond to a value sufficient to block the oscillator. During the nonoscillating condition, the capacitor C_2 discharges through the resistance combination until the negative biasing voltage is again sufficiently low to allow the tube to oscillate. This action is repeated cyclically at a rate which depends upon the time-constant of the resistance-capacitance network, which, as is evident, controls only the duration of the nonoscillating period.

In the absence of the modulating oscillator, the carrier oscillator would operate continuously. However, when the modulating oscillator begins to oscillate, its plate begins to draw current and a negative pulse is applied (through the coupling capacitor C_3) across the resistor

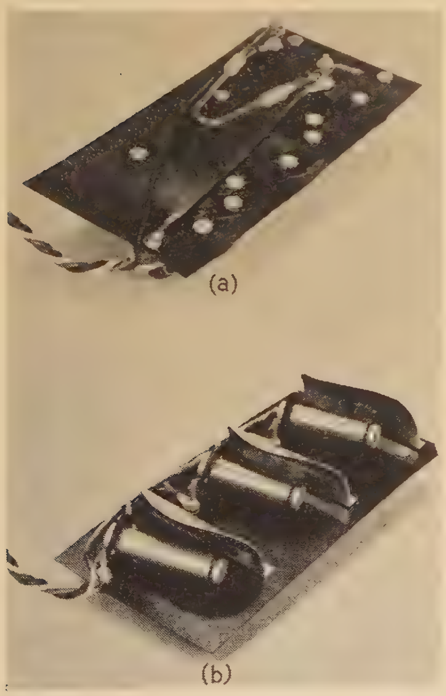


Figure 4. The temperature and humidity measuring elements

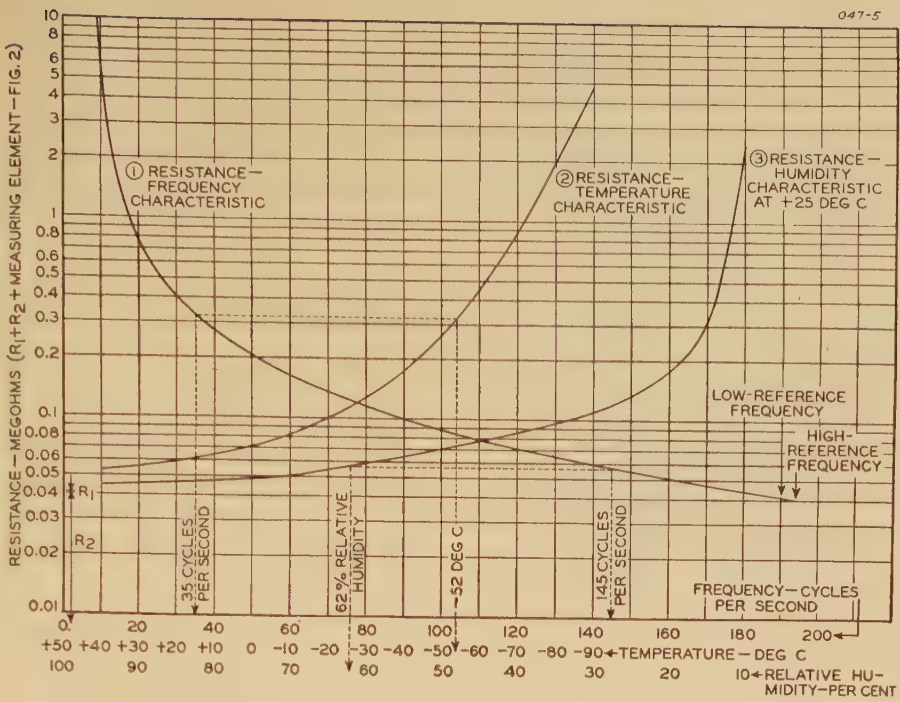


Figure 5. Curves illustrating the principles involved in the measurement of temperature and humidity

R_5 in the grid circuit of the carrier oscillator. This voltage is of sufficient magnitude to block the carrier oscillator; the carrier-frequency oscillations do not begin again until the modulating oscillator ceases to draw plate current (because of cessation of its oscillations) so that a positive pulse is applied to R_5. It will be evident from the foregoing that the carrier wave sent out by the radio-sonde transmitter is interrupted for short periods of constant time duration, the rate of occurrence or frequency of these interruptions being controlled by the value of the resistance in the resistance-capacitance network.

2. The Pressure-Switching Unit

This unit performs two functions, one as a measuring instrument of barometric pressure in the specified range, the other as a switch which connects into the resistance-capacitance circuit of the modulating oscillator, the temperature and humidity resistors and two fixed values of resistance known as the low and high reference. (See figures 2 and 3.) The pressure arm carries a tapered contact which bears against the polished face of a switching element at a position controlled by the ambient pressure. As the balloon rises into lower levels of pressure, the diaphragm expands laterally thereby sweeping the contactor over the face of the switching element and making the desired connections.

The switching element consists of 80 metallic strips separated by insulating strips. The conducting strips are arranged in groups of four adjacent intermediate contacts, the adjacent groups being separated by wider index contacts. The intermediate conducting strips are all connected together and to the field coil of a miniature relay which is energized upon completion of a low-voltage circuit by contact of the pressure-arm contactor with any of the intermediate conducting strips. The grounded armature of the relay normally rests against its back contact to which is connected one side of the temperature resistor. When the coil of the relay is energized, its armature bears against a front contact to which is connected one side of the humidity resistor.

By reference to figure 2, it will be evident that the relay operates to connect into the resistance-capacitance network of the modulating oscillator (in series with R_2 and R_1) either the resistance thermometer or the resistance hygrometer, depending upon whether the pressure-arm contactor bears against an insulating strip or an intermediate conducting strip of the switching element. The intermediate conducting strips are more conveniently referred to as humidity contacts since the time constant of the resistance-capacitance network and, hence, the modulating frequency of the radio-sonde transmitter is controlled by the resistance hygrometer when the pressure-arm contactor bears against any one of these contacts.

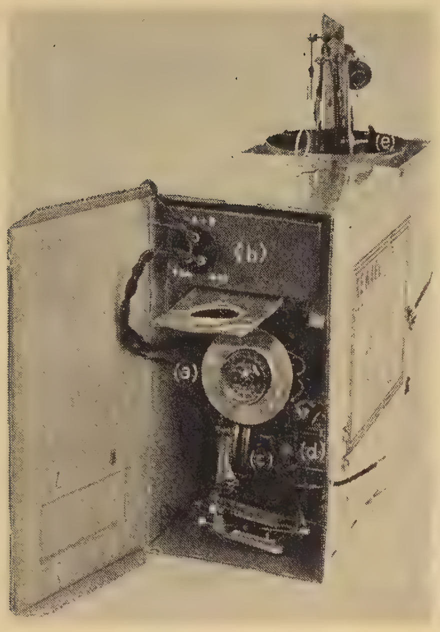


Figure 6. Radio-sonde component elements in their container

The index conducting strips of the switching element are arranged in two groups; the members of one group being connected electrically to the junction of resistors R_2 and R_1, and the members of the second group to the junction of R_1 with the two measuring elements. Contacts of the first group, comprising contact numbers 15, 30, 45, 60, and 75, are termed the high reference contacts, since only one resistor R_2 remains in circuit when the pressure-arm contactor bears against one of these contacts and, hence, a fixed high reference modulating frequency is obtained. Contacts of the second group, comprising contact numbers 5, 10, 20, 25, 35, 40, 50, 55, 65, 70, and 80, are termed the low reference contacts, R_2 and R_1 being in circuit when the contactor bears against one of these contacts and a somewhat lower fixed reference modulating frequency being then obtained.

3. The Measuring System

The method employed for measuring and indicating at a remote point the values of the pressure, temperature, and humidity encountered by the radio sonde during the ascent of the balloon is now evident. The radio-sonde transmitter emits a radio wave modulated by audio frequencies which correspond successively to temperature and humidity observations. The temperature observations occur when the pressure-arm contactor passes over an insulating strip while the humidity observations are obtained when the contactor bears against a humidity contact. The changeover from temperature frequencies to humidity frequencies occurs as the pressure-arm contactor just reaches a humidity contact. When the contactor reaches successive fifth contacts, the humidity observation is replaced by one of two fixed reference frequencies depending on whether a high or low reference contact is reached.

The sequence of switching operations serves as indication, by actual count, of the particular contact being reached by the pressure-arm contactor and, thus, from prior calibration, of the actual ambient pressure. This count is much facilitated by the occurrence of the high reference frequency every 15th contact and of the low reference frequency at intervening fifth contacts. In this usage, the reference frequencies serve as index points on the pressure scale.

To evaluate the temperature and humidity observations at the ground station, it is necessary to measure the received modulating frequencies and to interpret the measurements in terms of the resistance-frequency characteristic of the radio-sonde transmitter and the resistance-temperature and resistance-humidity characteristic of the temperature and humidity elements in the radio sonde. Fortunately, for this method of measurement, it is readily possible to control the manufacture of the three elements involved (the transmitter, the temperature tube, and the electrical hygrometer) so as to attain substantially uniform characteristics. Thus, the necessity for individual calibration of the three component elements is obviated and standard charts and scales may be used in evaluating the observations at the receiving station.

The principles involved in the measurement of temperature and humidity are illustrated in figure 5. Here curve 1 is the resistance-frequency characteristic of the modulating oscillator, curve 2 is the resistance-temperature characteristic of the temperature tube, and curve 3 is the resistance-humidity characteristic of the electrical hygrometer. In later sections of this paper, it will be shown that the measurements are actually made on the basis of relative frequencies rather than on an absolute frequency basis as might be inferred from the foregoing explanation. In this way, rather large tolerances may be allowed in the manufacture of the radio-sonde transmitter without affecting the accuracy of the measurements.

4. The Temperature Element

This device, shown in figure 4, utilizes the effect of temperature on the conduction of electricity through an electrolyte. Its construction is quite simple, as will appear from the following.

The glass capillary tube has an over-all length of 5 centimeters, a bore diameter of 0.875 millimeter, and a wall thickness of 0.4 millimeter. Capillary lengths of the required bore are purchased to a tolerance of ten per cent and, by volumetric measurements, their lengths are adjusted so as to produce an electrical resistance of 14,000 ohms (plus or minus five per cent) when filled with a standard electrolyte at +30 degrees centigrade. The capillary tubes are then bent into V form and are furnished with two glass bulbs fused to the ends. The wells provide for low-resistance contact between the electrolyte and the copper terminals of the tube, which extend through organic seals. One of the terminals consists of a very fine copper tube through which the capillary tube is filled in a vacuum chamber; the end of this copper tube is soldered to complete sealing of the device.

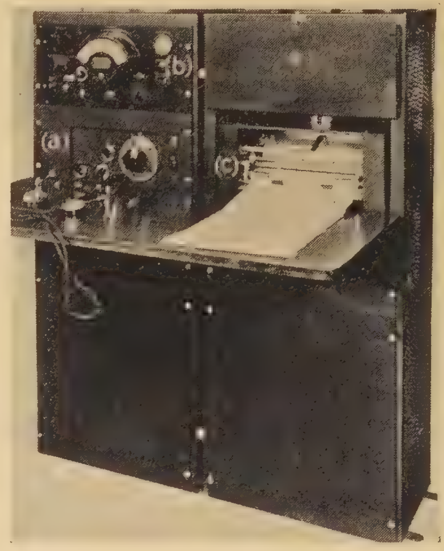


Figure 7. Ground-station receiving and recording equipment

The standard electrolyte used consists of a solution of 24 per cent (by volume) concentrated hydrochloric acid, 76 per cent of ethyl alcohol, and 2.7 grams of cuprous chloride for each 100 cubic centimeters of the resultant mixture. The alcohol lowers the freezing point of the electrolyte to below −100 degrees centigrade, while raising the resistivity to the desired value. The cuprous chloride operates in combination with the copper terminals to eliminate polarizing action in the tube when passing direct current.[2]

The resistance-temperature characteristic of the tube is shown by curve 2 in figure 5. Provided that excessive direct current is not passed through the tube,

its calibration remains constant within 0.5 per cent for a period of a year or more.

Advantages of the device for radio-sonde application include: uniformity of calibration for all tubes filled with the standard solution, large area of exposure to the ambient temperature, rapidity of response to temperature changes, and thermal isolation from other parts of the radio sonde with consequent reduction of errors in measurement due to heat conduction to a negligible order.

5. The Electrical Hygrometer

This device,[3] shown in figure 4, utilizes the effect of moisture on the conductivity of a hygroscopic salt. Three units are required to give the desired variation of resistance with relative humidity. The units are mounted on the opposite side of the mounting plate from the temperature tube and rain shields are provided to prevent direct contact with rain. Each unit consists of a dual winding of number 38 American wire gauge bare palladium wire (25 turns each with a pitch of 8 double turns per centimeter) wound on a coil form one centimeter in diameter. The coil form consists of an aluminum tube having a wall thickness of 0.25 millimeter and covered with an insulating coating (0.25 millimeter thick) which is highly resistant to water. After winding, the three units are each coated with different predetermined solutions of lithium chloride in polyvinyl acetate.

The surface-leakage resistance between the two interspaced windings of each unit varies with relative humidity according to predetermined characteristics. The most sensitive coating (3 per cent lithium chloride) covers the humidity range from 10 to 35 per cent; the next sensitive coating (2 per cent lithium chloride) covers the humidity range from 25 to 50 per cent; while the least sensitive coating (1 per cent lithium chloride) covers the humidity range from 40 to 100 per cent. By connecting the three units in parallel (with suitable resistors in series with the 2 per cent and 3 per cent units), the resistance-humidity characteristic shown by curve 3 of figure 5 is obtained.

This characteristic holds only at room temperature, the range of variation of resistance being modified as the temperature decreases. This results in a progressively narrower range of humidity indication at the lower temperatures; the range at −60 degrees centigrade is from 100 to about 35 per cent relative humidity.

The electrical hygrometer has important advantages over other forms of hygrometers, particularly for radio-sonde application. In an earlier form of the radio sonde described in this paper, a variable resistor controlled by the more conventional hair hygrometer is used for measuring relative humidity. While useful observations are obtained, there are two limitations to this type. The first is that the hair hygrometer does not function efficiently at temperatures below about zero degrees centigrade; the second, that even at higher temperatures it does not respond sufficiently to the sharp changes in humidity encountered by a balloon ascending at the lowest practical rate (175 meters per minute). The electrical hygrometer overcomes both of these defects. It is characterized by a very rapid response to humidity variations at temperatures down to at least −60 degrees centigrade. Its rate of response is sufficient to permit any practical balloon ascension rate, as has been determined in actual tests at ascension rates of up to 400 meters per minute.

6. The Complete Radio Sonde

A photograph of the complete radio-sonde assembly is shown in figure 6. A light cardboard case, covered with a metallic foil and divided into two compartments, is employed. The front compartment houses the radio transmitter *a*, the plug-in battery power supply *b*, the pressure-switching unit *c*, and the miniature relay *d*. The rear compartment supports the radiation shield *e*, for protecting the temperature and humidity elements from heating by solar radiation. The shield consists of two thin concentric aluminum tubes, the inner one of which supports the mounting plate on which the temperature and humidity elements are fastened. The shield normally extends about two centimeters above its compartment and the top edge of the mounting plate is normally flush with the top edge of the shield. The temperature and humidity elements are ventilated by the flow of air through this shield produced by the upward movement of the balloon.

The complete instrument weighs slightly less than one kilogram and its present unit price in quantities of several thousand is $27. An interesting feature of the instrument is that, with the radiation shield assembly slid down into its cardboard container, top and bottom flaps (tied back during the ascent) may be used for closing off this container. The instrument is then in convenient form for shipping or for return through the mail upon its recovery. Complete mailing instructions and the reward offered for its return are printed on the foil cover.

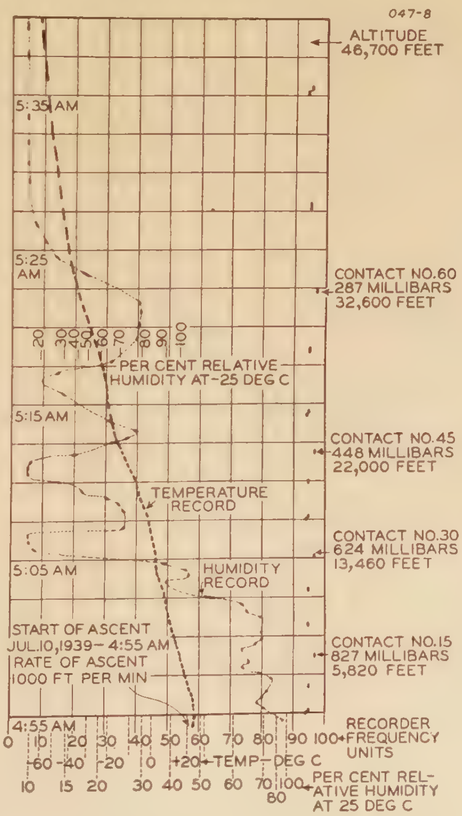


Figure 8. Record of a typical sounding

III. Ground-Station Equipment

Typical ground-station receiving and recording equipment are shown in figure 7. The receiving set *a* feeds an electronic frequency meter *b* which measures the frequency of the modulating signal from the balloon and converts it into a direct current proportional to the frequency. This is indicated by a microammeter on the electronic frequency meter and is simultaneously recorded by a recording microammeter *c*.

An important operating feature of the electronic frequency meter is that the current is directly proportional to the frequency within very narrow limits. Moreover, a control in the output circuit allows adjustment of the current corresponding to any frequency within the range by up to ±15 per cent without upsetting the linear relationship between the current and frequency throughout the range. The use made of this property is an essential feature in the use of the radio-sonde system described, as will appear later.

IV. Record of a Typical Sounding

A record of a typical sounding, redrawn for reproduction, is shown in figure 8. The start of the record, corresponding to

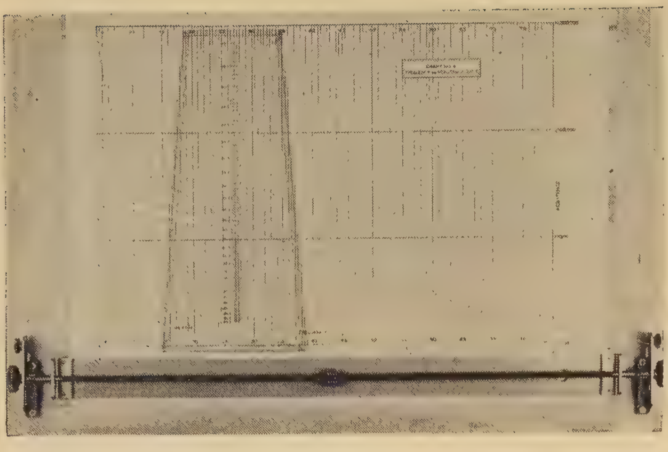


Figure 9. Illustrating the method of correlating the standard radio-sonde resistance-frequency characteristic with the standard resistance-temperature characteristic of the temperature tube

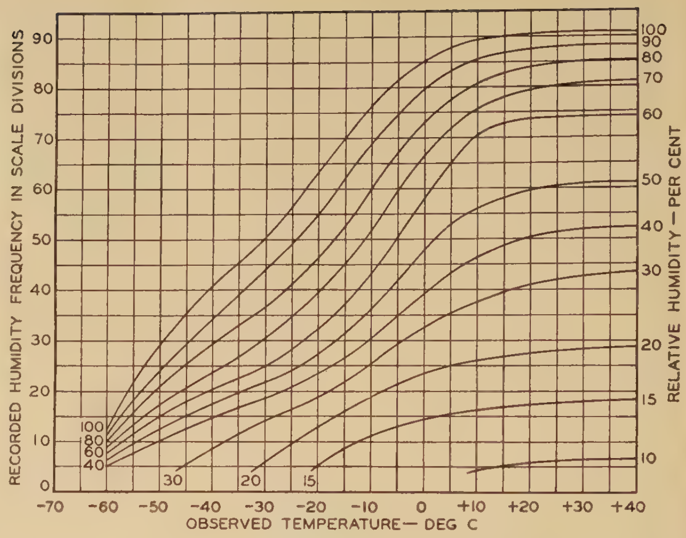


Figure 10. Charts for evaluating the relative humidity from the observed recorder frequency and the temperature at which the observation is made

the release of the balloon, is at the bottom of the chart. The recorder chart has 100 equally spaced divisions corresponding to a full-scale range of 200 cycles per second; however, it is more convenient for station personnel to work in terms of the recorder divisions which may be considered as arbitrary frequency units. For an approximate interpretation of the record, a scale of temperatures (for an average temperature bulb) and scales of humidities (at two ambient temperatures) are marked on the chart.

The traces at the extreme right of the chart represent the high reference frequencies while the traces just to the left of these represent the low reference frequencies. The physical positions of the pressure-arm contactor as these marks were being traced by the recorder may be visualized by referring to the contact numbers shown at the lower edges of the high-reference traces. (See also figures 2 and 3). The altitude of the balloon corresponding to each high-reference trace is marked on the chart as of likely interest to the reader. Altitude is determined from the air density computed on the basis of the pressure, temperature, and humidity observations.

The temperature and humidity traces are seen to form broken lines which plot, respectively, the variation of these two meteorological factors as a function of the balloon altitude. The temperature traces are readily distinguishable from the humidity traces by the nature of their variation. Each interruption of the temperature plot designates that the pressure-arm contactor has just reached a humidity or reference contact; each interruption of the humidity plot indicates that the contactor has just left a humidity contact. Light dotted lines have been added between adjacent humidity traces to emphasize the sharp variations obtained.

1. Evaluation of Pressure, Temperature, and Humidity

In determining the exact pressure level at which a given temperature or humidity trace obtains, the aerologist refers to the calibration chart for the particular pressure unit used. In this chart, heavy horizontal lines represent the reference contacts on the switching element and lighter horizontal lines represent the humidity contacts. The line thickness and spacing between lines are proportioned to correspond respectively to the widths of the conducting and insulating strips comprising the switching element. The ordinate scale thus represents contact numbers; the scale of abscissas represents barometric pressure in millibars. The calibrating points are generally taken just as the pressure-arm contactor reaches the reference contacts and a smooth line is drawn through them.

A special chart and glass scale are used for evaluating the temperature observations corresponding to particular recorder traces. The curve on the chart is the standard resistance-frequency characteristic of the radio-sonde transmitter plotted on semilogarithmic paper. The ordinate (logarithmic) scale represents resistance added in series with R_2 and R_1 in figure 2; that is, the resistance of the temperature tube. The scale of abscissas is in arbitrary frequency units corresponding to divisions on the recorder chart.

Since the temperature tube follows a fixed law of variation of resistance with temperature, the curve on the chart may also be considered to represent a plot of temperature versus generated audio frequency for a standard temperature tube and transmitter. However, in order to reduce the requirements as to the accuracy of the bore in the manufacture of the temperature tubes, the resistances of different tubes at a given temperature may differ appreciably even though they have the same temperature coefficient of resistance. This, in effect, requires that the temperature ordinate scale be permitted to slide up or down along the resistance scale. The required condition is met by mounting the chart on a drawing board and providing a glass plate bearing a vertical index line graduated in degrees centigrade which moves up or down on the chart. See figure 9.

The chart and scale together form a plot of temperature versus frequency, with means for sliding the temperature scale of ordinates to fit individual tubes. The lower edge of the glass scale rests against a movable horizontal crossbar (fastened to the drawing board) which facilitates making the adjustment.

Just prior to the release of a radio sonde, the operator measures the true temperature at the ground surface and the corresponding frequency observation from the radio sonde. These data are used in setting up the glass-plate temperature scale on the standard resistance-frequency characteristic. The operator moves the glass plate horizontally on the frequency chart so that the vertical index line coincides with the frequency corresponding to the observed recorder trace and then slides the crossbar on the drawing board upward or downward until the observed surface temperature intersects the resistance-frequency characteristic.

The chart used for evaluating the humidity observations is shown in figure 10. The ordinate scale is in arbitrary frequency units corresponding to divisions on the recorder chart. The scale of ab-

scissas represents the temperature at which the humidity measurements are made. The graphs represent curves of equal relative humidity. Knowing the frequency of the observed humidity trace and the corresponding observed ambient temperature, the relative humidity is determined by interpolation on the chart. Reasonable control of the manufacturing processes makes it possible to obtain electrical hygrometers which conform very closely to the standard characteristics of figure 10, within plus or minus three per cent relative humidity.

V. Accuracy of the Observations

1. Analytical Considerations

It will be evident that the accuracy of the pressure observations of sounding will depend practically entirely on the accuracy of repetition of performance of the pressure diaphragm and pressure-arm linkage. Repeated calibrations of individual units show agreement of the calibration points within two millibars. A control for moving the switching element laterally with respect to the pressure-arm contactor provides for setting the unit to read correctly at the surface pressure prior to an ascent, thereby correcting for zero shift and at the same time applying a surface correction for temperature effect at ground-level pressure. The over-all temperature effect in service use is within three millibars.

The accuracy of the temperature and humidity observations depends on a number of factors which at first hand would appear to require considerable control of the component elements employed in the radio sonde and at the ground station in order to secure the required accuracy. However, simple expedients operate to reduce the tolerances to practicable values.

One expedient is to make the measurements in terms of relative rather than absolute frequency. For this purpose, the low reference frequency, having a nominal value of 190 cycles per second (95 recorder divisions), is used as a control point. From the discussion in connection with figure 2, it is apparent that the measurement of audio frequency is made merely as a convenient way of measuring the ratio of the resistance of the temperature or humidity elements to the resistance of the low reference resistor. The parameters of the vacuum tube and of the modulating oscillator circuit and the variation of these parameters even for the wide variations of plate and filament voltages and ambient temperature encountered during a sounding have but little effect upon the ratio of any two frequencies corresponding to two values of the resistance network. Similarly variations in C_2 have negligible effect upon such ratios. It is obvious then, that if the value of (R_2+R_1) is maintained within ± 0.5 per cent under operating conditions and the current control in the output of the electronic frequency meter (in the ground-station equipment) is adjusted so that the recorder reads 95 divisions whenever the low reference signal is received, the observed frequencies corresponding to particular resistance values of the temperature- and humidity-measuring elements must have predetermined relationships to the low reference frequency. This is equivalent to saying that all radio-sonde transmitters may be made to have practically identical resistance-frequency characteristics whether in the laboratory or during an ascent merely by close control of (R_2+R_1). (The resistor R_6 being much higher than the other resistors, needs be controlled only within plus or minus five per cent.)

Thus, if the absolute reference frequency of a particular transmitter happens to be considerably different from the nominal value, the operator merely adjusts the frequency-meter control to make it read the standard nominal value. The same is true if the reference frequency drifts during a sounding. The small step variations in several of the low-reference traces on the record of figure 8 show where such adjustments were made.

Such small departures from the average characteristic as are found to occur in individual transmitters (after the reference-frequency adjustment is made) invariably take the form of a practically parallel shift of the curve upward or downward. The method of setting up the temperature scale on the basis of the surface-temperature data (described in a previous section) takes care of these departures in so far as the temperature measurements are concerned. A little consideration will show that, with this method, not only is the actual resistance of the temperature tube at the surface temperature taken into account, but a correction is automatically applied for the parallel departure of the actual resistance-frequency characteristic from the standard characteristic. While this correction does not apply to the humidity measurements, the requirements of accuracy of the humidity measurements do not demand such refinements.

Let us now consider what requirements must be met by the electronic frequency meter and the recorder in the ground-station equipment. The essential requirement is that the output current of the electronic frequency as indicated on the recorder trace shall be substantially linearly proportional to the received signal frequency and shall repeat this relationship within ± 0.3 division under all conditions of operation. This condition must be fulfilled regardless of the actual value of the reference frequency and represents a maximum error in temperature measurement of 0.5 degree centigrade at zero degrees centigrade. Small deviations from the required linear relationship may be taken care of by applying a suitable correction factor to the standard resistance-frequency characteristic used with a given ground-station setup or, even if neglected, is largely corrected for (in temperature measurements) by the process of setting up the temperature scale just described in connection with the surface-temperature check.

On the basis of the foregoing discussion, it is apparent that temperature measurements to an accuracy of ± 0.75 degree centigrade can be made with the radio-sonde system without placing undue manufacturing and calibration restrictions on either the radio sonde or the ground-station equipment.

2. Experimental Results

The curves of figure 11 provide experimental corroboration of the foregoing conclusion.[4] Curve 2 summarizes the results of 25 nearly simultaneous radio and airplane soundings. Some 100 such simultaneous ascents were made with practically the same order of agreement. The abscissas represent deviations be-

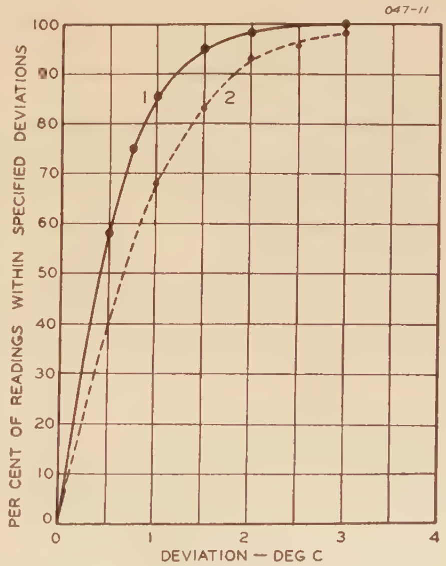


Figure 11. Summary of comparative data obtained: (1) with simultaneous radio-sonde and balloon meteorological soundings; (2) with simultaneous radio-sonde and airplane soundings

tween the two types of observations while the ordinates represent the percentages of the total observations falling within the specified deviations. In considering the results, it should be noted that the deviations include the effect of errors in the airplane instrument as well as in the radio sondes. Also, since the pressure measurements within the two types of instruments were required in computing altitude in order that the temperature observations might be compared at equivalent altitudes, the deviations include the effect of possible errors in the observations of pressure.

Curve 1 summarizes similar results for 20 soundings in which the balloon carried a recording meteorograph in addition to the radio sonde; the data from this recording instrument were obtained only after recovery. The better agreement shown by curve 1 is attributed to the fact that both instruments were tied together whereas, in the case of curve 2, the balloon was often carried away by winds up to 50 miles from the airplane at the upper levels.

In curve 1 temperature comparisons down to about −50 degrees centigrade are averaged, while in curve 2 the comparisons include data down to −30 degrees centigrade.

Similar data for the accuracy of measurement with the electrical hygrometer cannot be presented because of the lack of a standard for comparison. As nearly as can be determined on the basis of checks against a psychrometer in a controlled chamber, the electrical hygrometers agree within about three per cent relative humidity at temperatures down to about −15 degrees centigrade. Comparisons with hair hygrometers carried in airplanes show reasonable agreement down to temperatures at which the hair becomes sluggish (about −5 degrees).

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Lightning Protection of Wood-Pole Lines

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Synopsis: The reliability of wood-pole transmission lines during the lightning season has long been a problem with operating companies. To meet the ever increasing service demands approximately 60 miles of line were reconstructed using the inherent insulation of a wood-pole line with lightning protector tubes on one of three conductors. Two years' experience with this type of construction has shown better than a 90 per cent reduction in lightning outages.

A REVIEW of the past nine years' performance on the 26-kv wood-pole lines of the Public Service Electric and Gas Company indicated that approximately 79 per cent of all interruptions were caused by lightning which represented about 38 lightning tripouts per 100 miles of line per year. This compared to a rate of 3.1 for 132-kv steel-tower lines.

After unsuccessful attempts to improve the lightning performance of wood-pole lines by the use of ground wires or wood insulation, lightning protector tubes were installed on a single-circuit 26-kv line. This line is part of a three-phase system with the neutral grounded through a 75-ohm resistor which limits the single-phase-to-ground fault currents to somewhere between 200 to 500 amperes. Since the three-phase short-circuit currents are as high as 10,000 amperes it was impossible to meet the range of currents between single-phase and three-phase faults with a single tube and a four-tube scheme would be necessary.[1] In order to reduce the cost, tubes were selected having a 60-cycle current rating of 200–1,000 amperes.

In the absence of any records at the time it was thought that the number of phase-to-phase operations would be very small. Experience showed that many of the lightning strokes involved more than one phase, resulting in the failure of a number of tubes due to the high phase-to-phase short-circuit currents. Although the number of outages was not decreased with this scheme there was very little damage to any of the transmission-line equipment and the time of outage was decreased materially.

This three-phase installation was tried for two seasons with no reduction in the number of lightning outages. In 1937 the line was rebuilt to make one phase a shielding conductor by locating it so that the remaining phases would be shielded from direct strokes. Lightning currents were drained from the shielding conductor by means of lightning protector tubes. The remaining phases were isolated from the shielding conductor and tube ground circuit by insulation sufficient to prevent phase-to-phase faults. This allowed the use of a single tube designed to withstand only phase-to-ground currents which were much less than phase-to-phase currents.

The performance of this line during the 1937 lightning season indicated that the method of protection was satisfactory but that the tubes used (15,000 to 30,000-ampere impulse current rating) would not withstand the lightning currents encountered. This conclusion was based upon the large number of tubes that failed on single-phase line outages with no phase-to-phase currents involved.

In 1938 new tubes of a greater lightning-current rating (100,000 amperes) were installed. In addition, two more lines were rebuilt to the same type of construction, making a total of 18.9 cir-

Table I. Wood-Pole Lightning-Protection Performance

	1938	1939
Miles of line (circuit)	18.9	59.4
Number of tubes installed	341	830
Tripouts	1	0
Intermediate poles flashed	0	0
Shielded phases flashed	0	0
Tube insulator flashed	1	0
Tubes destroyed	1	0
Tubes operated but failed to protect	1	0
Tubes operated correctly	103	108
Total number of tubes operated	105	108

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1. For all numbered references, see list at end of paper.

cuit miles. In 1939 an additional 40.5 circuit miles of line were rebuilt.

Performance

The performance of these lines during the 1938 and 1939 lightning seasons is given in tables I and II.

Table I shows the operating record, by years, of the lines rebuilt for lightning protection. The absence of intermediate-pole and shielded-phase flashovers indicates that the method of application is very satisfactory; also the very high per cent correct tube operation shows that the current rating of the tubes as now used is apparently satisfactory.

Table II is a comparison of the lightning performance of these lines before and after lightning protection was installed.

In order to eliminate the effect of variation in lightning severity in different territories and years, table III was made up to show the comparison between standard and protected wood-pole lines. By putting the lines on a common basis the operating records for the years 1938 and 1939 are compared for unprotected and protected lines in the same territory. The comparison shows a reduction of about 80 per cent for 1938 and 100 per cent for 1939 in the number of lightning outages and time of interruption.

The construction used followed the original design[2] which showed an estimated reduction in lightning outages of approximately 75 per cent. Although two years' experience indicates a greater reduction in outages it is expected that a variation in intensity and number of storms will result in less improvement than the 100 per cent obtained this year.

Table III. Comparison of the Lightning Performance of Protected and Unprotected 26-Kv Wood-Pole Lines in the Same Lightning Area

	1938 Unprotected	1938 Protected	1939 Unprotected	1939 Protected
Miles of line (circuit)	48.7	18.9	53.3	59.4
Lightning tripouts	13	1	13	0
Minutes interruption	19	1	266	0
Tripouts per 100 miles	26.7	5.3	24.4	0
Minutes interruption per 100 miles	39	5.3	500	0
Reduction in outages with lightning-protection construction (per cent)		80.3		100
Reduction in minutes interruption with lightning-protection construction (per cent)		86.4		100

Table II. Comparison of Transmission-Line Performance Before and After Installation of Lightning Protection

	Before 1930–37	After 1938	After 1939
Circuit miles	63.3	18.9	59.4
Total thunderstorm line days*	3,180	150	215
Total lightning outages	204	1	0
Tripouts per 100 miles per yr	36.6	5.3	0
Tripouts per storm line day	0.64	0.0067	0
Tripouts per storm line day per 100 miles	1.02	0.035	0
Reduction in outages per 100 miles per yr by protection (per cent)		85.5	100
Reduction in outages per storm line day by protection (per cent)		98.9	100
Reduction in outages per storm line day per 100 miles by protection (per cent)		96.6	100

* An index of storm exposure which is the sum of the number of thunderstorm days as determined for each line individually.

Design

The design of lightning protection of low-voltage transmission lines incorporating high insulation strength and a shielding phase conductor with a lightning protector tube was presented in an earlier paper.[2] In brief, this system of protection is accomplished as follows:

1. One phase of each circuit is made a shielding conductor by locating it so that the remaining phases will be shielded from direct strokes.

2. Lightning currents are drained from the shielding conductor by means of a lightning protector tube.

3. The remaining phases are isolated from the shielding conductor and tube ground circuit by insulation sufficient to prevent phase-to-phase faults. This allows the use on each structure of a single tube designed to withstand only phase-to-ground currents which, in general, are much less than phase-to-phase currents.

Lightning Protector Tubes

One of the advantages of this type of protection co-ordinated with the neutral-grounding impedance is that the variation in operating conditions and future system growth and its effect upon the currents to which the protector tube may be subjected may be neglected. This is not the case when protector tubes are installed on all three phases. The lines upon which these tubes were installed are a three-phase system nominally rated 26.4 kv with the neutral grounded through a 75-ohm resistor. In one network there are two neutrals operating. In many cases if the protector tubes were to be applied to all three phases it would have been necessary to use four protector tubes where three protector tubes of a high current rating are connected in star and the star point connected to ground through a protector tube of lower current rating.[1]

In addition, where the line is long or the system is extensive, the short-circuit currents of the lines may vary widely and zoning the tubes would have been necessary had they been installed on all three phases.

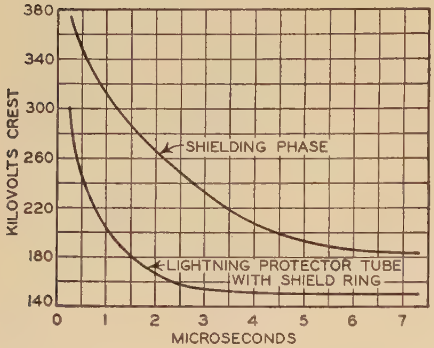
Since the single-phase-to-ground fault current is limited to a value of somewhere between 200 and 500 amperes, a tube was selected having a 60-cycle current rating of 200 to 1,000 amperes and an impulse discharge current rating in the order of 100,000 amperes. These tubes were used throughout the 26-kv system for all single-phase lightning protection. In order to have the tube function properly with the system under consideration the minimum internal tube gap permitted by the manufacturer was $6^1/_4$ inches.

In order further to decrease the cost of protection a simplified tube was used. It was felt that the life of protector tubes is dependent upon weathering of the fiber and erosion of the bore during operation and that expensive hardware was not warranted. For this reason a tube was designed using standard galvanized pipe fittings for hardware and a nail electrode. Five years' experience with tubes of this type has not shown any reason for a change to more expensive hardware.

Impulse tests using standard ($1^1/_2$x40-microsecond) positive and negative waves were made on each pole top, with and without the tube electrode in place, in order to obtain volt-time breakdown curves of the pole-top assembly and tube as installed in the field. It was found that with 45-kv pin-type insulators without wood in series there was not sufficient margin between tube breakdown and insulator flashover for all points on the curves and that in some cases the curves

actually crossed. This was verified by observation when the insulator flashed over without tube breakdown. Since it was necessary in rebuilding some of the lines to increase the height of the poles with a steel extension bracket, it was not practical to insulate the tube mounting and ground from the insulator pin. It was found that a shield ring installed on the tube would lower the impulse breakdown of the tube, so that within practical limits, all points on the curves were at least ten per cent below the minimum breakdown values of the shielding phase. In practice shield rings were used on all tubes where the mounting was such that there was less than six inches of wood in series with the insulator and a grounded connection.

Figures 1 and 2 are typical volt-time breakdown curves of the single- and double-circuit pole tops respectively. These are composite curves made from several sets of test data and show the margin of protection between the tube and the shielding-phase breakdowns.



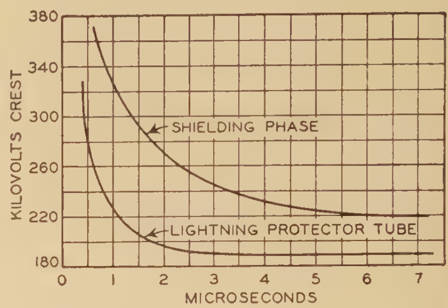


Figure 1 (left). Volt-time breakdown curves, single-circuit protected pole, $1^1/_2$x40-microsecond positive wave

Figure 2 (right). Volt-time breakdown curves, double-circuit protected pole, $1^1/_2$x40-microsecond positive wave

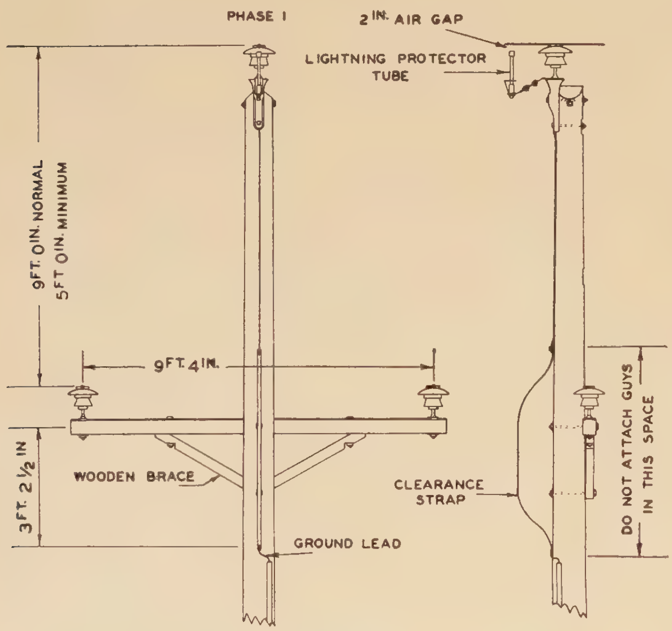


Figure 3. Single-circuit pole top, protected pole

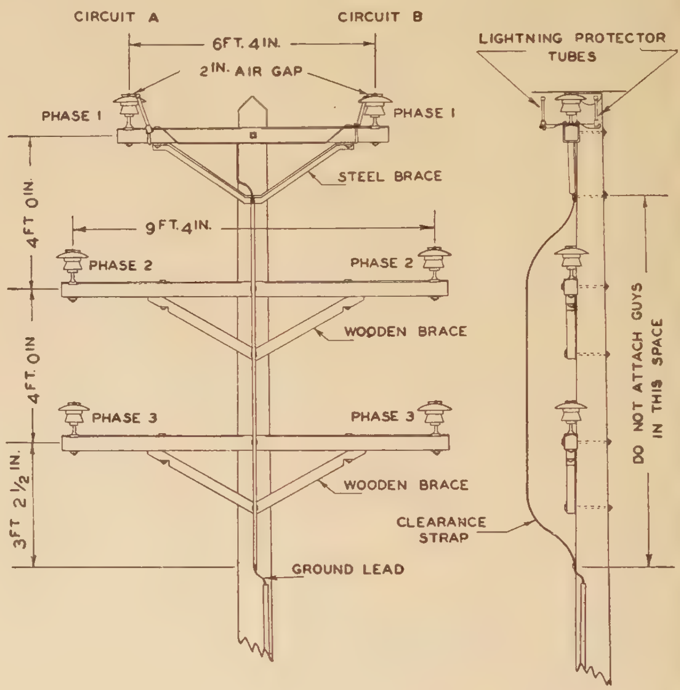


Figure 4. Double-circuit pole top, protected pole

Construction

An attempt was made to keep as much similarity as possible between protected and unprotected poles from both construction and appearance standpoints. It was also thought desirable to have a single-circuit pole that could be expanded to a double-circuit pole with only minor construction changes. In order to obtain the most economical construction the insulation between the shielding or struck conductor and its ground lead was coordinated with each of the shielded conductors, and to ground, for the various pole-top assemblies.

In order to conserve space in this paper photographs of the actual construction are not included. It was felt that drawings giving dimensions and other information would be far more valuable.

Figure 3 shows the assembly of a single-circuit protected pole top. It will be noted that the tube ground was brought down the pole by means of a clearance strap in order to increase the insulation between the tube ground and the unprotected phase wires which in turn increased the permissible distance between protected poles.

The unprotected pole is similar to figure 3 except that the tube, mounting bracket, and ground lead were eliminated and all grounds such as guys were attached at least two feet below the bottom crossarm.

The arrangement of the double-circuit protected pole top is shown in figure 4. Again the unprotected pole is similar except that the tubes, mounting brackets, and ground lead were eliminated with the highest guy connection two feet below the bottom arm. In addition a wooden crossarm brace was substituted for the steel brace shown on the top arm.

Location of Protector Tubes

The duty of a lightning protector tube is, in the event of short-time overvoltages, to prevent flashover between phases and flashover to ground, other than through

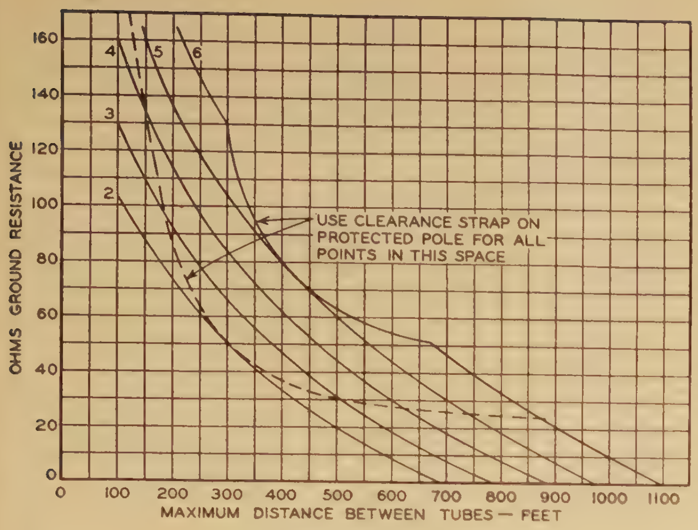


Figure 5. Curves showing required location of lightning protector tubes, single-circuit pole line

Numbers on curves are minimum distance in feet of guy below bottom arm on unprotected pole

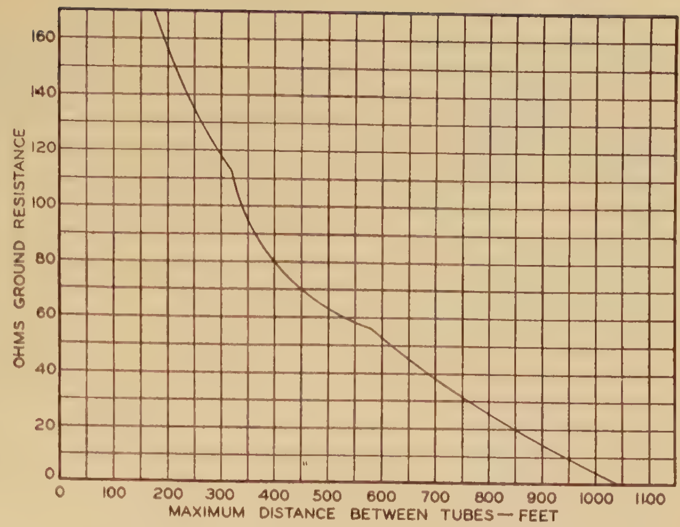


Figure 6. Curves showing required location of lightning protector tubes, double-circuit pole line

the tube. It must accomplish this protection on the structure upon which it is installed, called the "protected pole," and on adjacent structures called "unprotected poles."

This protection is dependent upon the insulation of the various structure assemblies, the resistance of the tube grounds, and the distance between the tube installations. These conditions were taken into account, both for the protected and unprotected poles, in determining the required location of tubes as given on the following curves.

Figure 5 is for a single-circuit line and shows the allowable distance between protected poles as dictated by the ground resistance of the tube grounds and the location of guy attachments. Since guy locations are determined by local field conditions a family of curves is included to provide for the pole in the section, between protected poles, having the least insulation to ground. As mentioned previously, the clearance strap is installed on the protected pole in order to increase the insulation between the tube ground and the protected phase wires. This strap is not always necessary as indicated by the dotted line on figure 5. For example no clearance strap is needed if the ground resistance is below 24 ohms or if there is an unprotected pole in the section which requires a guy as close as two feet below the bottom arm.

Similarly figure 6 gives data for a double-circuit line based upon the use of a clearance strap on all protected poles. Because of the protected-pole limitation there is no advantage in attaching guys on the unprotected poles more than two feet below the bottom arm.

Two years' operating experience with this type of lightning protection has confirmed the conclusions given in the paper presenting the original design.[2] At the present time it is planned to rebuild an additional 90 circuit miles in 1940 to be in operation for the coming lightning season so that further experience will be obtained.

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2. Lightning Protection for Transmission Lines, A. W. Gothberg and A. S. Brookes. Electrical Engineering (AIEE Transactions), volume 56, January 1937, pages 13–16.

Discussion

E. Piepho (The Detroit Edison Company, Detroit, Mich.): The authors have presented a good case for lightning protection on wood-pole transmission lines using protector tubes on a high-shielding phase wire. However, reduction of lightning tripouts alone will not justify the expenditure for this type of protection in all cases. Other factors such as maintenance expense, the number of actual service interruptions occasioned by lightning tripouts as compared with tripouts due to other causes, duration of service interruption, etc., must be fairly evaluated. In cases where the line serves as a tie in the transmission network, its opening will not necessarily result in a service interruption and is, therefore, of small consequence if it can be immediately reclosed. Generally speaking, lightning damage does not prevent reenergizing the line within a minute or less, so that even when service interruption occurs it is of short duration. Interruptions due to wind, trees, equipment failure, or public interference, while not very frequent, are much more likely to hold the line out for a considerable time.

On The Detroit Edison Company 24-kv system the five-year operating record for 1,000 miles of overhead lines shows an average of 28.5 lightning tripouts per 100 miles per year. Of this number, 10.5 lightning tripouts per 100 miles per year caused service interruptions of five minutes or less, and only one caused a service interruption exceeding five-minutes' duration. This latter figure compares with 1.4 service interruptions exceeding five minutes due to other causes previously mentioned. It is doubtful whether tube-arrester protection can be justified for the entire system to eliminate so few service interruptions due to lightning, although in the case of a few lines the application of protector tubes appears to be a good investment. Three such lines were equipped with protector tubes in 1939, the selection having been based on line maintenance cost due to lightning, and the importance of the service supplied by the line.

In addition to this protector-tube application, tube arresters were installed on 24-kv pole-top switches in 1938. One-hundred-forty switches were selected for this protection, the selection having been determined by the past operating record of these switches with respect to lightning damage. During the 1939 storm season this protection functioned at an average rate of 1.3 times per switch protected. Only one switch suffered damage due to failure of the tube arresters. This was caused by failure of the protector tube to clear follow current due to excessive tube erosion, which may have been caused by multiple or continuing lightning strokes.

These tubes were inspected last autumn and several removed because of excessive erosion. It appears that isolated installations of protector tubes such as these result in more rapid erosion than has been reported for installations of tubes distributed along a line.

Two protector tubes were found with their bores partly plugged by mud and foreign material such as used by wasps. It is possible that such obstructions may account for the ruptured tubes reported by some users.

H. P. Sleeper (Public Service Electric and Gas Company, Newark, N. J.): Because of the economics involved, open-wire wood-pole transmission-line construction has constituted in the past, and probably will continue to constitute in the future, the bulk of high-power transmission systems in this country. For that reason the lightning protection of such lines has formed the subject of innumerable papers presented before this Institute. It is probably safe to predict that means for combatting this problem will continue to accumulate in the records of this Institute and the files of the United States Letters Patent Office.

It is, therefore, refreshing to review a paper which does not invent a new device but which merely applies an old one in a novel manner to secure improved operation. Such is the subject of the paper on "Lightning Protection of Wood-Pole Lines" by Messrs. Sels and Gothberg, and if the results quoted are any indication of the expected performance, it would seem that the operating results should be meritorious and the economics very favorable.

A study was made by this discusser in connection with the transmission system described by the authors to determine whether the scheme described in this paper, or a Petersen coil, should be applied to improve operation. A study of faults was made from oscillographic data obtained over a considerable period of years. The type of transmission construction involved consisted of a triangular arrangement of phases with two phase wires on top and a 36-inch spacing.

Obviously this construction favored the occurrence of short circuits due to lightning. The cable portion of the complete transmission system constituted 30 per cent of the total mileage. Results over a five-year survey showed that 80 per cent of all faults occurred on the open wire and bus sections of the system, and 20 per cent on the cable section. Furthermore, only 21 of the 80 per cent open-wire and bus faults started to ground. As a matter of interest, 16 of the 20 per cent cable faults started to ground. Hence it was apparent that the 21 per cent of all faults was all that could be eliminated by any scheme of ground-fault extinction. Hence if 90 per cent correct operation were granted to either Petersen-coil operation or expulsion-tube operation, it would still leave 80 per cent plus faults to be relayed out. On this basis the installation of a Petersen coil was not considered economically justifiable. On a program of gradually rebuilding the transmission lines, however, the preferred construction as shown in the authors' paper was practically as cheap as any other and the full effect of the expulsion-tube operation could be obtained at once on the rebuilt lines. On that basis the protective-tube scheme was approved.

This scheme of open-wire transmission construction has distinct advantages:

1. All single-phase-to-ground faults should be extinguished in not more than one cycle of arcing time. In this feature it should compare directly with the operation of a Petersen coil.

2. It should not affect in any way the operation of existing protective relays on the lines. If relays are in use which will respond to short-circuit impulses of one cycle or less, as is the case on the system in question, it will be necessary to delay the tripping of the breaker for that length of time to avoid incorrect operation during the time of tube operation. A scheme for doing this was described by me in the past and is published. (See page 292, Electrical Engineering, 1938.) The same is true of a Petersen-coil installation.

3. With a high-impedance system neutral in use, as the 75 ohms in the neutral of the system described by the authors, the duty on the tubes does not increase with changing generating capacity in service due to time of day or changing load growth with the years. To a certain degree only, this is also true of a Petersen-coil installation.

Probably the greatest contribution to the continuity of service to the customers of electric utilities today and in the near future is, and will continue to be, the installation of fault-extinguishing devices of some kind on high-voltage transmission lines. Today the two types which have been compared in these comments present interesting possibilities, and existing systems, and particularly systems constructed hereafter, should be capable of capitalizing on their proved capabilities. If a choice must be made as to which system to employ, a study of each individual case seems to be the only answer. If existing line construction is considered satisfactory, or if major reconstruction is not to be made, the Petersen coil will, in this commentator's opinion, prove to be the cheaper to install and maintain. However, it is this writer's opinion that serious consideration should be given to the installation of both types of protection on a given system for the following reasons:

1. The duty on the expulsion tubes would be reduced and longer life should result.

2. Smaller tubes could be used on high capacity systems because of the reduced recovery voltages.

3. Ground faults on busses would be extinguished, which is not accomplished by tubes. This should make the installation of bus differential relay protection unnecessary, except on the very most important busses, since almost all bus faults originate to ground. The economics of this possibility may be paramount.

L. E. Merrow (Rockland Light and Power Company, Nyack, N. Y.): The Rockland Light and Power Company, after considering protection to about 90 circuit miles of 33-kv delta transmission lines of both wood-pole and steel construction, installed a Petersen coil last spring. The territory covered by these lines is north of Public Service Electric and Gas Company, which is above the New Jersey-New York border and has about the same amount of lightning.

Since the coil was installed over 60 per cent of the line disturbances were caused by lightning and 52 per cent of these were extinguished by the action of the coil. The remainder of the disturbances causing trip-outs were either phase-to-phase or two-phase-to-ground. Since some of the wood-pole lines have flat construction, many of the phase-to-phase short circuits occurred on these lines. It is possible, however, that if these particular lines had been protected by rebuilding each pole as suggested in Mr Sels' paper, the operation of the coil might have been more satisfactory.

F. Von Voigtlander (The Commonwealth and Southern Corporation, Jackson, Mich.): The authors, following the earlier paper on this subject by A. W. Gothberg and A. S. Brookes, present interesting and valuable data on the development of the idea of converting one conductor of a line into a combination phase and shielding wire.

The writer would like to ask to what extent this combined phase and shielding conductor has provided direct-stroke protection for the line such as might be evidenced by reduction in structural damage due to lightning.

The double-circuit construction shown in Figure 4 appears to employ quite conventional spacing and is similar to the design proposed in the 1937 paper. The single-circuit construction as shown in figure 3, however, places the shielding conductor at a considerable height above the other two and in this respect departs markedly from the conventional as well as from the previous proposed design. What factors led to the adoption of the present single-circuit design?

Whenever the use of the conductor as a combination shield wire is proposed, the treatment of the transpositions must be given consideration if the possibility of two-phase-to-ground faults is to be avoided. Various schemes have been proposed to meet this problem. What features have the authors incorporated in their design to take account of the presence of transpositions in the protected line?

E. J. Allen (General Electric Company, Pittsfield, Mass.): The paper by Messrs. Sels and Gothberg is a valuable addition to the field experience with protector tubes, particularly since it describes a substantial application of protector tubes on the top phase or phases only.

This scheme of protection is fundamentally the same as that for the overhead ground wire, since under impulse conditions the top protected phase acts as an overhead ground wire by discharging through protector tubes to ground. Hence, the same fundamental requirements apply as to adequate shielding to unprotected conductors, low ground resistance, and sufficient clearance at mid-span, which govern overhead-ground-wire practice.

Since other operating companies may wish to consider lightning protection of lines by protector tubes on top conductor only, the curves figure 1 of this discussion have been prepared to show the allowable stroke current (two microseconds to crest) through different ground resistances at the protected structure with various impulse flashover values from ground wire to shielded phase conductors. This is based upon the flashover formula[1] described in the appendix of this discussion. A coupling factor of 0.22 was used which appears to be reasonable for the cases presented by the authors, and the relatively negligible effect of normal-frequency voltage was neglected.

Table I was based on 250-foot separation of protector-tube installations, corresponding to tubes on the top phase only at every structure if the span length is 250 feet; or a tube at every other structure if 125-foot spans are used. With the 250-foot separation of protector tubes and two-microsecond lightning-current front, reflections from adjacent protected structures will reduce the voltage and if flashover to shielded phase occurs, it will occur at approximately two microseconds for a stroke between protected structures and at

2 to 3.5 microseconds for stroke to protected structure.

Figure 1 enables analysis under two conditions:

(a). Stroke between protected structures

(b). Stroke to protected structure

The curves, figure 1, show the advantage of wood crossarm braces and the clearance straps on lower phase (or phases) of protected structures to increase the impulse insulation as described in the paper. For structures, as for example, a protector tube at each structure, the impulse voltage to cause mid-span flashover corresponds to the air strike distance between conductors at mid-span.

In the example previously considered, where the shielded conductors of a protected structure had a line-to-ground flashover of 400 kv and a ground resistance of 25 ohms, an intervening unprotected structure without down leads may have a line-to-line flashover of 500 kv or more.

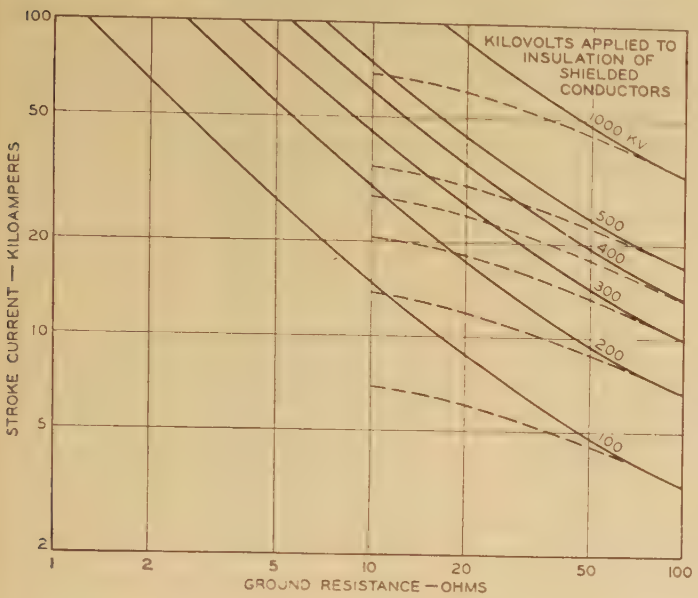

Figure 1. Effect of stroke current upon potential applied to insulation of shielded conductors for various ground resistances of protected structure

Two - microsecond front; protected structures 250 feet apart

Solid curves—Stroke to protected structure

Dashed curves—Stroke between protected structures

example, for stroke to the protected structure (solid curves) with currents not over 30,000 amperes, an increase in the insulation flashover of shielded conductors from 200 to 400 kv permits ground resistances of 25 ohms instead of 10 ohms. If the flashover level is but 200 kv and ground resistance 25 ohms, the protection would be had for lightning currents up to only 15,000 amperes.

Where the advantages of protector tubes having high discharge current capabilities of 100,000 amperes are to be fully realized, both the effect of high insulation of shielded conductors and low grounding resistance must be utilized if protector tubes are applied to top phase or phases only. For example, for strokes to protected structure of 100,000 amperes, the ground resistance required to prevent flashover of 400 kv lower-phase insulation is 5.5 ohms.

The dotted curves, figure 1, show the similar relationships when a stroke occurs between protected structures. As the authors point out, where intervening unprotected structures do exist, use should be made of available wood insulation between line insulators and ground, eliminating any grounded objects at the top of the structure, as for example, guy wires or down leads to ground. For example, a structure of the type shown in figure 3 of the paper not having a protector tube or a down lead to ground would have a higher flashover voltage $V(t)$ owing to the longer flashover path from top phase to shielded phases. This voltage (dotted curves) should be used in figure 1 when considering the stroke as occurring between protected structures. Where there are no intervening unprotected

If the flashover level is 500 kv, the dotted curve shows protection would be afforded the shielded conductors up to 28,500 amperes for 25-ohm ground resistance as compared to 30,000 amperes permissible stroke current to protected structure. By increasing the insulation level between protected structures, this has the advantage of making the line capable of withstanding stroke currents of the same order of magnitude at mid-span as at the protected structure.

The maximum stroke currents which can be permitted at and between protected structures, obtained from figure 1, can be referred to a curve showing frequency of occurrence of various lightning current magnitudes in service.[2] From this the percentage of strokes which the line can handle without flashover can be obtained.

In the two cases investigated, strokes between and at protected structures were considered separately and methods given for estimating them. Actually, however, the stroke may hit the line at any point. Since the nature of the problem hardly justifies a separate investigation for each point on the line where the lightning may strike, it can be assumed, on the average, any stroke within a quarter of the distance of separation between protected structures will be equivalent to a stroke at the structure with the solid curves figure 1 applying, while strokes within similar distance from a mid-point between protected structures are evaluated by the dotted curves, figure 1.

Where protector tubes are applied on all three phases, the protection afforded is independent of ground resistance, the latter values are important only in so far as they affect the single line-to-ground power follow current during tube discharge, and the selection of the minimum-current interrupting rating of the protector tube.

Table I of the paper shows in 1938, 105 operations of the 341 installed tubes were recorded, or 30.8 per cent. The tube operations were 5.7 per mile per year. In 1939, 108 operations of 830 tubes installed were recorded, or 13 per cent, corresponding to only 1.8 operations per mile per year. The total thunderstorm line days, however, had increased to 215 (1939) as compared with 150 thunderstorm line days during the preceding year. The variability between the number of operations of protective devices and the number of thunderstorm days is not unusual. It may be partially accounted for, however, if the storms experienced in 1939 were localized over a small zone of the 59.4 circuit miles of line where protector tubes were installed.

Appendix

The flashover formula derived by Bewley is:

$$V=(1-C_n)aR'I+e$$

in which

V = voltage across the insulation

C_n = coupling factor (depends upon the number, configuration, and spacing of the conductors, and is modified by corona)

a = crest factor (depends upon the length of spans or the distance between protector tubes, structure footing resistance, lightning wave front, and conductor surge impedance)

R' = effective resistance (depends upon the grounding resistance, and the surge impedance of the lightning stroke and of the stricken conductors)

I = lightning current which the stroke could deliver to a zero-resistance ground (which is equal to twice the traveling-wave current in the stroke)

e = effective instantaneous normal-frequency voltage (depends upon the normal-frequency polarities and the conductors involved)

References

1. Protection of Transmission Lines Against Lightning: Theory and Calculations, L. V. Bewley. *G. E. Review*, April 1937, pages 180–8.

2. Lightning Investigation on Transmission Lines—VI, W. W. Lewis and C. M. Foust. Electrical Engineering (AIEE Transactions), January 1937, page 101, figure 1.

H. N. Ekvall (Philadelphia Electric Company, Philadelphia, Pa.): The paper by Messrs. Sels and Gothberg describes a very interesting application of protector tubes to 26-kv wood-pole lines and indicates that it has effected a reduction in line outages of 80 per cent and better. It should be noted, however, that in applying this scheme the insulation strength of the wood-pole lines was materially increased by changing to high ridge pin and twin vertical wire configurations, replacing metal with wood braces and relocating guys.

Experience on approximately 600 miles of 13- and 33-kv wood-pole lines of the Philadelphia Electric Company during the past

five years indicates that such increases in the wood insulation strength alone (without application of protector tubes) can effect large reductions in trouble. For example, on 13-kv lines, changeover from flat-top to ridge-pin configuration, relocation of guys, and use of wood braces to take better advantage of the wood-pole insulation have been largely responsible for an 89 per cent reduction in line interruptions per 100 circuit miles during the period 1935 to date. Similarly good performance has been obtained on the 33-kv lines.

The principle of protection employed by the Philadelphia Electric Company is to minimize the formation of power arcs following lightning flashover by increasing the length of wood insulation between phases and between phase and ground up to certain minimum values. This principle of protection has proved effective as indicated above. Power arcs are the chief source of trouble, while lightning itself seldom causes more than slight splintering on the pole or crossarm.

Based on the Philadelphia Electric Company operating experience, it is estimated that the protected 26-kv lines referred to in this paper would have shown a reduction in outages of the order of 80 per cent due to their increased insulation alone, with protector tubes and ground wires omitted. It appears, therefore, that much of the benefit to line performance probably comes from the increased insulation and that a small improvement may come by addition of the protector tubes.

The authors indicate that it is planned to rebuild an additional 90 miles of line in 1940 with increased insulation and protector tubes. In order further to verify the benefits of wood insulation referred to above, it is suggested that on some of the rebuilt lines the ground wires and protector tubes be omitted. This will permit a comparison of the performance of high insulation with and without protector tubes.

Edward Beck (Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): Messrs. Sels and Gothberg are to be congratulated on at least two counts. Two years ago one of the authors in collaboration with Mr. Brookes published a paper in which the use of one phase wire equipped with tubes was proposed as a ground wire for the circuit. This in itself was a departure from usual practice, and the authors are to be complimented for their initiative in risking the innovation. But further than this, they made calculations two years ago and predicted a reduction of 75 per cent in lightning outages. This was a bold statement at the time. That it was carefully considered and based on sound logic is indicated by the fact that their predictions have more than been fulfilled. We note, however, that now they are more conservative and are careful to state that they do not expect the 100 per cent record to continue. It would add to the completeness of the paper and thus to its value, if the data and premises on which the curves of figures 5 and 6 are based were reproduced also.

The first paragraph mentions about ten times as many line tripouts on the wood 26-kv as on the steel 132-kv circuits. The ground-wire protection on the 132 kv, no doubt, makes much difference. The paper illustrates that a high degree of immunity to lightning outage can be achieved either by proper ground-wire or tube application.

This paper and the one of two years ago together constitute a good example of the solution of a lightning problem by applied engineering.

G. E. Dean (Public Service Electric and Gas Company, Newark, N. J.): In discussion of the paper by Messrs. Sels and Gothberg, I wish to present some of the aspects of field application.

The 26-kv wood-pole transmission of the Public Service Electric and Gas Company contains many miles of single-circuit single-crossarm flat-configuration construction. In order to adapt the new configuration where one phase wire is elevated, considerable rearrangement of the pole top is necessary in addition to the relocation of guys. Where sufficient pole height is present the pole-top pin is used. With this construction, where there is no wood insulation between the insulator pin and the tube base, a shield ring is used to lower the breakdown voltage of the tube. The intermediate pole is identical but is without tube or ground wire. Where there is not sufficient pole height a steel pole extension is used and again the shield ring for the tube is required. The intermediate pole is again identical with the omission of the tube and the ground lead.

The shield ring used with tube assemblies where there is no wood insulation between the insulator pin and the tube base reduces the breakdown voltage of the $6^1/_4$-inch internal gap by redistributing the electrostatic field around the tube. The ring design is simple and rugged, consisting of three legs to support the ring; these legs in turn being welded to a large washer base. The washer of the shield ring fits over the pipe nipple at the base of the tube so that the ring assembly is slipped over the tube base and the tube installed in the normal manner.

Existing double-circuit poles are of either the two-crossarm triangular configuration or the three-crossarm vertical configuration.

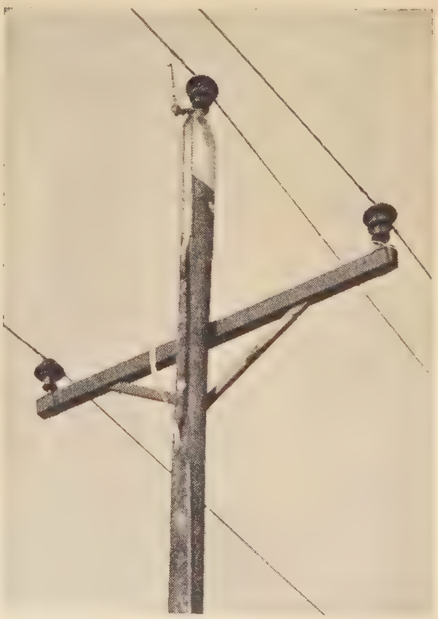

Figure 2. Single-circuit protected pole

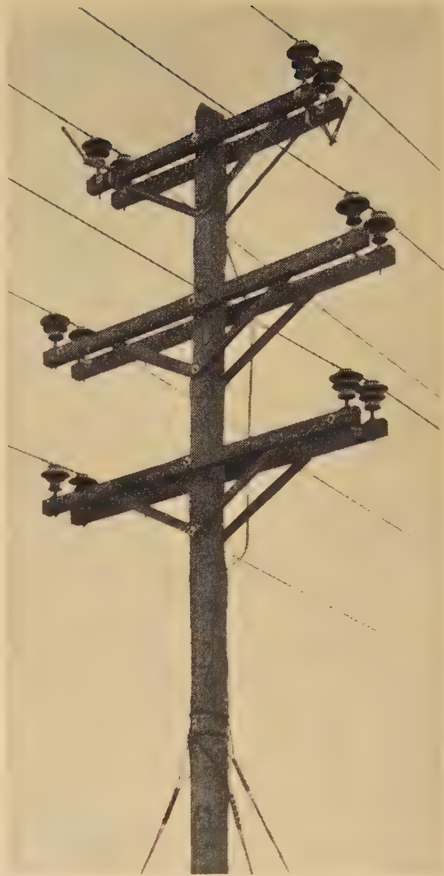

Figure 3. Double-circuit protected pole

Since the new construction is of the three-crossarm type considerable rearrangement may be required. Side guys may be attached to the end of the top crossarm when tubes are used or, in all other cases, must be well below the bottom crossarm. Either the tube or the intermediate pole may of course be double armed for strength requirements without affecting the protection. During the work of the last few years, poles of insufficient height have been replaced with a higher pole but design and test work has been completed on a joint which will permit a wood-pole section supporting one crossarm to be spliced on top of an existing pole. Much of this work will be done during the 1940 program.

Where a tube is installed on a heavy angle pole using suspension type insulators it is necessary to increase the number of insulators on the lower phase wires and attach the guys either to the top of the pole at the tube base or well below the bottom phase. Where no tubes are installed on the corner pole the number of insulators on all phases is increased and the guys must be insulated.

The simplified tube mentioned in the paper consists of the horn fiber tube, itself consisting of concentric tubes of suitable outside diameter to accommodate one-inch pipe threads and the inside, or bore diameter, slightly over one-quarter inch as determined by the 60-cycle phase-to-ground current. The internal gap length is established by choosing a nail of the proper length to give $6^1/_4$ inches between the end of the nail and the washer at the grounded end of the tube. This internal gap length is of course determined by the flashover characteristics of the insulator to be pro-

tected and the recovery-voltage characteristics of the system on which the tube is used. The base of the tube, which is grounded, consists of a straight threaded pipe nipple which is inserted in a hole punched in the mounting strap. A lock washer and nut or nut and lock nut on the nipple below the strap completes the assembly.

It is not expected that this simplified tube will have a life, when exposed to the weather, equal to that of the more elaborate designs. However, the development of the expulsion gap is far from finished and designs have changed so materially that it is not felt necessary to adopt a design of long expected life. The installation of the tubes is made in such a manner that warping of the tube cannot close the external gap and result in the burning of the tube by power current and the tripout of the circuit. It is expected that these tubes will be repainted each three years during the regularly scheduled pole-top inspection.

H. K. Sels and A. W. Gothberg: The authors value the discussions offered and will attempt to close the paper as briefly as possible.

Edward Beck suggests that the data and premises on which the curves of figures 5 and 6 are based should be reproduced also. To include this information would be merely a repetition of a previous paper, reference 2 of the present paper. There have been no changes in the values used as can be borne out by figure 8 in the original paper which corresponds to figures 5 and 6 of this paper. Additional curves were added to figures 5 and 6 to provide for various locations of guy attachments on the poles and also to take advantage of the additional insulation provided by the clearance strap.

The economics of lightning protection is questioned by E. Piepho. It is not suggested that all electric operating companies should rebuild all of their lines to provide this type of protection, but it is felt that if lightning is any problem at all, new lines when constructed can be built to accommodate this protection and the tubes added at any time.

Interruptions of any kind are a hard thing to evaluate. Since transmission is one cog in the electric-utility field there are many associated benefits with this type of protection, such as a reduction in the duty of terminal equipment by lessening the number of tripouts, reducing the number of dangerous overvoltages in stations and adjacent cable sections, improved customer service and its effect on system planning. In considering the necessity of any type of lightning protection the isokeraunic level must be taken into account. There is no doubt that there are some sections of this country where an expenditure for any lightning protection could not be justified. The method of protection proposed is, in the authors' opinion, the most economical to date for the benefits derived and the justification for its economic application depends upon many considerations of the operating company.

E. J. Allen presented a curve, figure 1, showing the effect of stroke current upon the potential applied to insulation of shielded conductors for various ground resistances at the protected structure, with a given distance of 250 feet between protected structures. It will be found by referring to the paper presenting the original design (reference 2) and the results given in figures 5 and 6 of this paper, that they agree very favorably. We wish to thank Mr. Bewley for the time involved to show this agreement and it was upon his original methods that some of our analysis was based and led to the prediction of a 75 per cent reduction in lightning outages.

F. Von Voigtlander has asked to what extent this combined phase and shielding conductor has provided direct-stroke protection for the line as evidenced by reduction in structural damage due to lightning. Two years' experience, with a close examination of all pole tops, has shown no structural damage, indicating 100 per cent shielding effect. As evidence that direct strokes were encountered there were many cases of consecutive tube operations along the line. Anywhere from 5 to 11 tubes have operated in a row. In one particular case in 1938 a tube rated at 100,000 amperes surge current blew up without a line tripout, indicating power current did not cause the damage. In this case all tubes operated in a section of the line for approximately 3,500 feet. Mr. Von Voigtlander also points out that the present single-circuit pole top differs from the one proposed in the 1937 paper. The only difference shown is an additional four inches vertical separation of the shielding conductor above the other two conductors for "minimum" spacing. This change is brought about by a change in pole-top bracket, otherwise the dimensions are the same. The nine feet "normal" distance is used when a single-circuit pole may be converted into a double-circuit pole and the crossarm then becomes the lower crossarm of a double-circuit pole top by the addition of two crossarms and the elimination of the ridge pin. Reference has been made to the question of transpositions but nothing has been worked out to take them into account. Fortunately, low-voltage pole lines are usually short, as is the case of the lines involved in this instance, and no transpositions exist in the lines with this protection.

L. E. Merrow's discussion of his experience with a Petersen coil indicates the necessity of providing a drain point to ground for lightning currents when a coil is used, otherwise many phase-to-phase tripouts will result. This was pointed out in a discussion by one of the authors in AIEE Transactions, volume 57, 1938 (December section) page 672.

H. N. Ekvall states that on 13-kv lines of the Philadelphia Electric Company the use of wood insulation has been largely responsible for an 89 per cent reduction in line interruptions and that similarly good performance has been obtained on the 33-kv lines. He suggests that we rebuild some of the lines and omit the protector tubes to show that the increased wood insulation will give an 80 per cent reduction in outages. There is no doubt that the rebuilding of any line by providing more clearances and newer equipment will eliminate many tripouts of all causes. We have tried the use of wood insulation only, exactly as Mr. Ekvall has suggested without the 80 per cent reduction in line outages and found by experience that a good number of the strokes were causing wood splintering. Since this was a source of later trouble wood protector blocks were used in order to direct the wood splintering to a piece of equipment that could be easily replaced. It was then found that these wood blocks would blow up and result in a power arc.

If induced strokes only are to be considered we would agree with Mr. Ekvall but since direct strokes have to be accounted for and putting performance on a basis of outages per 100 miles per year rather than per cent improvement, which depends upon what you start with, we estimate 18 tripouts or cases of damage per 100 miles per year with wood insulation only as compared to 3 tripouts per 100 miles per year with tubes. Generally speaking, we think Mr. Ekvall is getting his protection in the deionizing action of the wood as indicated by the splintering so that the economics of his applying tubes depends upon the damage he is experiencing.

In connection with Mr. Sleeper's recommendations that serious considerations should be given to the installation of a Petersen coil and tubes on the same system, it seems to the authors that the tubes on a Petersen-coil system are entirely unnecessary with protected-phase-wire construction. As pointed out previously, arcing gaps should be provided between the top phase wire and ground to drain the lightning currents from the line. The attention of the manufacturers is called to the necessity for such a device.

We wish to thank Messrs. Dean and Sleeper for their contributory discussions and all of our associates for their share in making this development a success.

The Characteristics and Power Requirements of Spinning Frames—II

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THIS PAPER is a continuation of the investigation on the characteristics and power requirements of spinning frames presented at the AIEE North Eastern District meeting, Springfield, Mass., May 3–5, 1939, and published in this volume of AIEE TRANSACTIONS, pages 1–4 (January section).

The original investigation involved a 348-spindle Whitin frame with $1^1/_2$-, $1^3/_4$-, 2-, and $2^1/_4$-inch diameter rings operating at various speeds, and while the analysis indicated very definite characteristics and power requirements, the tests were not sufficiently extensive to conclude that the power formula developed would hold true for larger ring sizes and different-size yarns.

Further tests were therefore conducted on a 216-spindle Whitin frame, with $2^1/_4$-, $2^1/_2$-, $2^3/_4$-, and 3-inch rings spinning 10*s* yarn, and it is the analysis of these tests and their association with the previous tests that is now presented.

In comparing these recent tests with the original tests, it is immediately evident that the $2^1/_4$-inch ring is common to both and that they do not indicate the same power requirement. It is also evident that these two tests were made with different size yarns, and therefore, the formula submitted for the power requirements in the first paper cannot apply, inasmuch as it takes no account of yarn size.

The effect of yarn size on power requirements, other conditions being the same as indicated in figure 1, is definitely a factor to be considered in establishing a formula.

In figure 2, the relationship between yarn size and yarn weight is shown, and since the weight is so small and decreases so gradually in sizes smaller than 20*s*, it is doubtful whether it will affect the power appreciably in this range. In sizes larger than 20*s*, however, the weight increases rather rapidly, and should, therefore, be taken into consideration, but probably 4*s* yarn is about the largest generally made on spinning frames.

In figure 1, which covers the $1^1/_2$-, $1^3/_4$-, 2-, and $2^1/_4$-inch rings on the 348-spindle frame, and the $2^1/_4$-, $2^1/_2$-, $2^3/_4$-, and 3-inch rings on the 216-spindle frame, the power curves have all been reduced to a 216-spindle basis for the purpose of comparison, and in this comparison we have the following data to analyze for the effect of yarn size on power:

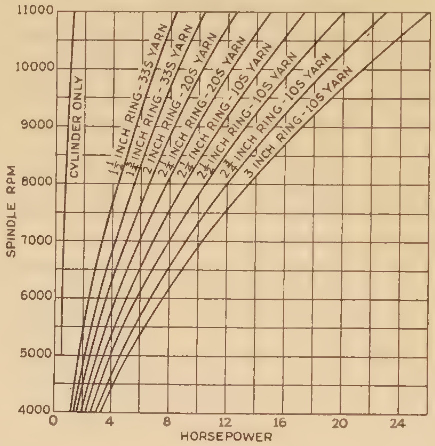

Figure 1. Power requirements of a 216-spindle spinning frame with different diameter rings and various yarn sizes, plotted from formula derived from test data

Ring Diameter (Inches)	Yarn
$1^1/_2$	33*s*
$1^3/_4$	33*s*
2	20*s*
$2^1/_4$	20*s*
$2^1/_4$	10*s*
$2^1/_2$	10*s*
$2^3/_4$	10*s*
3	10*s*

If we analyze each one of the curves separately, the power seems to vary as $(\text{rpm}/1{,}000)^{2.04}$, rpm being the spindle speed.

The spacing of these curves must depend on the ring diameter and the size of yarn, and if we consider frames on which the same size of yarn is spun and run at a fixed speed, it shows the power varies in accordance with 1.42 power of the ring diameter.

The other variable which enters the picture, namely yarn size, is evident in the power curves for the $2^1/_4$-inch rings with 10*s* and 20*s* yarn, and here the power appears to vary in accordance with

$$\frac{1}{\sqrt[4.75]{\text{yarn size}}}$$

from which we may develop the formula for power:

Horsepower per spindle =

$$\frac{0.0003055}{\sqrt[4.75]{S}} \times R^{1.42} \times \left(\frac{\text{rpm}}{1{,}000}\right)^{2.04}$$

where

S = yarn size
R = ring diameter in inches
rpm = spindle speed

Table II has been calculated using this formula. Ring sizes and yarn num-

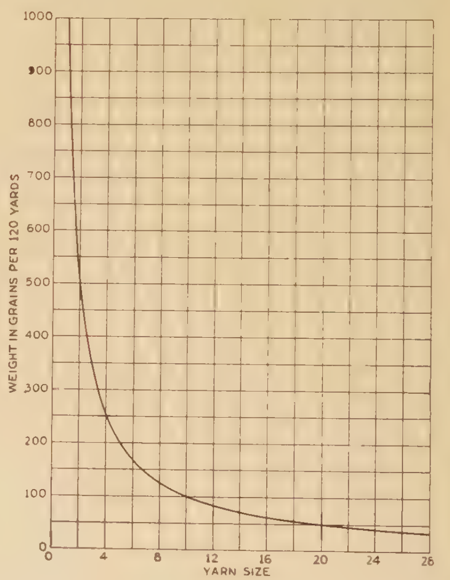

Figure 2. Relation between yarn size and weight

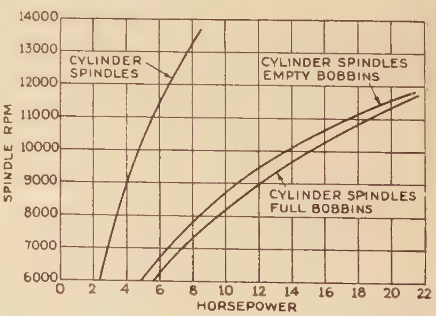

Figure 3. Breakdown test on 216-spindle frame, $2^1/_4$-inch-diameter ring

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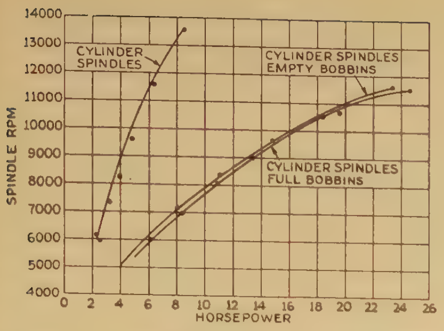

Figure 4. Breakdown test on 216-spindle frame, 2½-inch-diameter ring

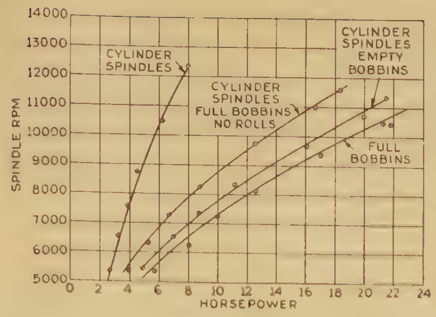

Figure 5. Breakdown test on 216-spindle frame, 2¾-inch-diameter ring

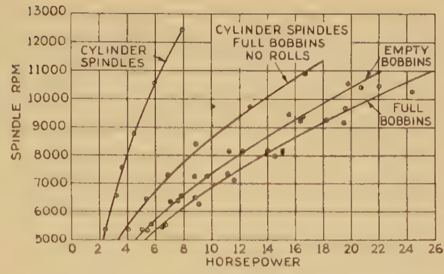

Figure 6. Breakdown test on 216-spindle frame, 3-inch-diameter ring

bers spun in cotton mills vary so widely that no attempt has been made here to cover all conditions, but the figures given will serve as a basis for the more common combinations.

Power readings were taken while spinning yarn at the empty-bobbin position, and again at the full-bobbin position for each diameter of ring, over a range of spindle speeds from approximately 6,000 rpm to 11,500 rpm, the upper range being considerably beyond the point of practical spinning, but as in the previous tests, this was necessary to establish the characteristics of the frame.

Figures 3 and 4 show the power requirements when spinning with 2¼- and 2½-inch-diameter rings, with medium-large spindles.

The power curve for the cylinder and bare spindles is also plotted.

Figures 5 and 6 show the power requirements when spinning with the 2¾- and 3-inch-diameter rings with the large spindles. It is interesting to note on the breakdown tests on these larger ring diameters that the power required to spin yarn at the empty-bobbin position was considerably more than the power required to drive the spindles with full bobbins, and without the front rolls running. This increase in power is accounted for in the windage and friction of the balloon of the yarn and the traveler.

From the results of both investigations it shows that the cotton-spinning frame

Table I. Spinning-Frame Tests—Frame Data

Type and model—*F*2, long draft
Number of spindles—216
Type spindle—large medium 2*K*, large 4*K*
Whorl diameter—1⅛ inches
Gauge spindle—4½ inches, four boss rolls
Width tape—⅝ inch
Traverse—8 inches

Cylinder diameter—10 inches
Cylinder bearings—all ball bearing six-section cylinder
Ring diameter—2¼, 2½, 2¾, and 3 inches
Type of ring—number 2 flange
Traveler weight and number—number 10 square point, Bowen
Number yarn spun—10*s*
Yarn spun—warp-filling wind
Ply roving—two ply—1.0 hank. Draft 20. Twist per inch 16.10
Type builder—four-point filling
Thread board—traversing

Diameter front roll—1 inch
Diameter middle roll—⅞ inch
Diameter back roll—⅞ inch
Tape idler pulleys—regular; weight used, 2½ pounds
Separators—solid aluminum
Weight on front rolls—4½ pounds

Gearing:

Cylinder—26 teeth
Jack—112 teeth
Twist—88 teeth
Front roll—100 teeth
Lay—53 teeth
Crown—140 teeth

Table II. Spindles Per Horsepower for Different Size Yarns at Various Speeds

Ring Diameter (Inches)	Spindle RPM	Yarn Size 6	8	10	12	14	16	18	20	30
1¼	12,000							27.4	28.0	28.0
	11,000							32.9	33.6	33.6
	10,000							39.7	40.6	40.6
	9,000							49.5	50.7	50.7
	8,000							63.0	64.5	64.5
	7,000							82.7	84.5	84.5
1½	12,000				19.4	20.0	20.6	21.1	21.6	
	11,000				23.35	24.1	24.8	25.4	26.0	
	10,000				28.15	29.1	29.9	30.7	31.6	
	9,000				35.3	36.5	37.4	38.4	39.2	
	8,000				44.7	46.2	47.5	48.7	49.8	
	7,000				58.5	60.5	62.2	63.7	65.2	
1¾	12,000			15.70	16.30	16.85	17.3	17.72	18.15	
	11,000			18.90	19.60	20.3	20.8	21.35	21.9	
	10,000			22.9	23.80	24.6	25.2	25.9	26.5	
	9,000			27.2	28.25	29.2	30.0	30.8	31.5	
	8,000			35.2	37.60	38.9	40.0	41.0	42.0	
	7,000			47.3	49.10	50.7	52.1	53.5	54.7	
2	12,000		11.44	12.4	12.87	13.3	13.68	14.0	14.35	
	11,000		13.78	14.9	15.5	16.0	16.42	16.85	17.27	
	10,000		17.20	18.0	18.7	19.35	19.9	20.4	20.9	
	9,000		21.46	22.5	23.3	24.1	24.8	25.4	26.05	
	8,000		27.20	28.5	29.6	30.6	31.4	32.2	33.0	
	7,000		35.7	37.3	38.8	40.0	41.2	42.25	43.25	
2¼	11,000	11.35	12.05	12.63	13.1	13.55	13.93	14.3	14.62	
	10,000	13.70	14.58	15.25	15.85	16.4	16.85	17.25	17.7	
	9,000	17.10	18.20	19.1	19.8	20.5	21.05	21.6	22.1	
	8,000	21.70	23.10	24.2	25.1	26.0	26.7	27.4	28.0	
	7,000	28.40	30.20	31.7	32.9	34.0	35.0	35.8	36.7	
	6,000	38.90	41.40	43.3	45.0	46.5	47.8	49.0	50.2	
	5,000	56.4	60.0	62.8	65.2	67.5	69.4	71.0	72.7	

Ring Diameter (Inches)	Spindle RPM	Yarn Size 2	4	6	8	10	12	14	16
2½	10,000		10.81	11.78	12.53	13.13	13.64	14.10	14,50
	9,000		13.50	14.75	15.65	16.40	17.04	17.60	18.05
	8,000		17.10	18.70	19.82	20 80	21.75	22.30	22.9
	7,000		22.40	24.4	26.0	27.20	28.25	29.20	30.00
	6,000		30.80	33.50	35.70	37.40	38.80	40.10	41.20
	5,000		44.50	48.6	51.60	54.2	56.20	58.00	59.5
2¾	10,000	8.17	9.45	10.3	10.95	11.47	11.9	12.30	
	9,000	10.17	11.76	12.82	13.65	14.3	14.85	15.34	
	8,000	12.92	14.95	16.28	17.3	18.16	18.8	19.42	
	7,000	16.95	19.6	21.3	22.7	23.8	24.7	25.50	
	6,000	24.1	27.9	30.4	32.3	33.9	35.1	36.25	
	5,000	33.7	38.9	42.3	45.1	47.2	49.0	50.60	
3	10,000	7.24	8.36	9.1	9.68	10.15	10.54		
	9,000	9.01	10.4	11.35	12.08	12.65	13.14		
	8,000	11.45	13.25	14.43	15.35	16.1	16.7		
	7,000	15.05	17.4	18.9	20.15	21.1	21.9		
	6,000	20.6	23.8	25.9	27.6	28.9	30.0		
	5,000	29.9	34.5	37.6	40.0	41.9	43.4		

Temperature Rise of Electrical Apparatus as Affected by Radiation

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ASSOCIATE AIEE

Synopsis: Radiation is generally of importance only in apparatus cooled by natural convection and radiation. If such apparatus with a smooth exterior surface is mounted in the sun and shielded from the wind, an additional rise as high as 20 degrees centigrade may occur. White or gray nonmetallic paints may decrease solar effects. Fins and corrugations increase the ratio of convected to radiated heat and thereby decrease radiant effects.

IN electrical engineering, radiation is relatively unimportant in the normal application of most apparatus, but in occasional applications it should be considered.

The subject of radiation has received considerable attention from heating and ventilating engineers.[1,2] It is always considered in computing the amount of refrigeration required for air conditioning. In this case, large areas are exposed to sunlight and small temperature differences are important. In the dissipation of heat from the human body, radiation is normally more important than convection and differences of a few degrees in wall temperature are important.[3]

In electrical engineering, motors, transformers, and similar apparatus operate at higher temperatures, so that a difference of a few degrees is not as important as in air conditioning. The effect of radiation on the temperature rise depends on the enveloping area of a device. In most devices the cooling obtained from a smooth surface is inadequate, so that finned or corrugated surfaces, forced air circulation, or water cooling are provided. Under these conditions the normal losses of the device per unit of enveloping area are large, so that the radiant effect of hot walls or the sun is small as compared to the normal losses. For such cases radiation will have a negligible effect on the temperature rise.

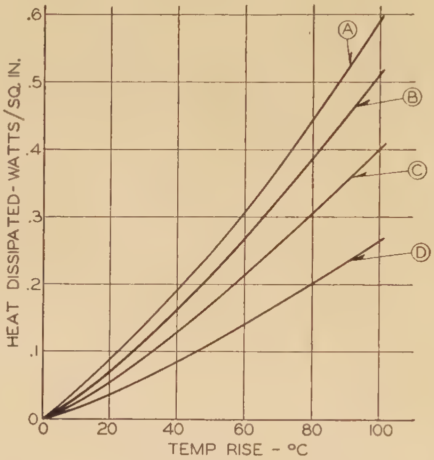

Figure 1. Heat dissipation–temperature rise curves

A—Radiation from black surface to black surrounding surfaces at 25 degrees centigrade

B—Natural convection from a large (two feet or over) surface facing upward

C—Natural convection from a large vertical surface

D—Natural convection from a large surface facing downward

However, some types of apparatus must depend for cooling on a relatively smooth external surface, and may be mounted in locations exposed to radiation from the sun or hot walls. It is the purpose of this paper to point out the relative magnitudes of these factors and to give curves which will be helpful in estimating the temperature rise under unusual circumstances where radiation is important.

Radiation of Heat

The basic law of heat radiation is that any object is radiating heat proportional to the fourth power of the absolute temperature, but all surrounding objects are likewise radiating. If the surfaces are partially reflecting, multiple reflections lead to complicated calculations.

In the case of a sphere or plane surface small as compared to the enclosing space, the heat loss from the small surface becomes independent of the emissivity of the enclosing surface because of multiple reflections within the enclosing

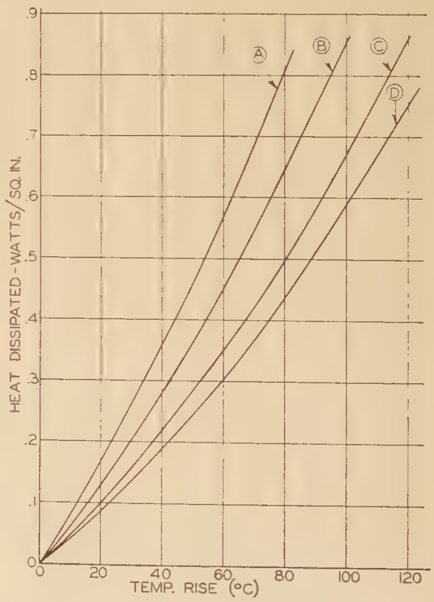

Figure 2. Heat radiated from a black surface

A—100-degrees-centigrade surrounding surface temperature

B—70-degrees-centigrade surrounding surface temperature

C—40-degrees-centigrade surrounding surface temperature

D—25-degrees-centigrade surrounding surface temperature

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1. For all numbered references, see list at end of paper.

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has a very definite speed-power characteristic which is not only affected by the number of spindles, but also by the ring diameter and the size of yarn spun. When these conditions are known, it is possible to predict, within reasonably close limits, the power required to drive a spinning frame.

There is a possibility that these machines, like most others, may vary slightly in power requirements even when so-called duplicates are involved. These variations should not affect the horsepower rating of the motors selected to drive the frames, and these data should be of considerable help to the machine manufacturer and the textile manufacturer in selecting the proper-size motor for applying to spinning frames within the scope of these investigations.

space. The heat loss from the small surface is that given by the familiar Stefan-Boltzman law.[15,4]

$$W=36.9e_1\left[\left(\frac{\theta_1}{1{,}000}\right)^4-\left(\frac{\theta_2}{1{,}000}\right)^4\right]$$

W* = energy radiated, watts per square inch
θ_1 = temperature of radiating surface (degrees Kelvin)
θ_2 = temperature of the enclosing surface (degrees Kelvin)
e_1 = emissivity of the small surface

The emissivity of any surface is equal to its absorption coefficient. Also, $1-e=$ reflectivity.

If the radiating object becomes of appreciable size as compared to the enclosing surface, the emissivity of the enclosing surface becomes of importance since, in a reflecting enclosure, radiation from the sphere will be reflected back onto the emitting surface. A. D. Moore[4] has evaluated the heat loss for several typical cases of this type and also the increase in radiation due to grooves or corrugations in reflecting surfaces. Another complication is that in general the emissivity of a surface varies with the wave length of the radiation. For example, white paint reflects a large percentage of solar radiation but is a good absorber for low-temperature radiation. In the case of irregular partially reflecting surfaces, exact calculations are usually too complicated for engineering purposes.[5] Fortunately, most electrical apparatus is painted with a nonmetallic paint which has an emissivity of the order of 0.9 for long wave lengths. The effective surface for radiation is then approximately the same as the enveloping surface. Radiation is in general not of importance in apparatus which is cooled by fans or is water cooled. In dealing with apparatus cooled by natural convection and radiation which must be located adjacent to hot surfaces, it usually is sufficient to compare the relative magnitudes of radiation and convection on the test floor with those calculated for service conditions and from these estimate the temperature under the service conditions. Natural convection varies widely, depending on the shape of the surface and surrounding objects. However, curves are available which give the convection under average conditions, and for many engineering purposes these values will prove sufficiently accurate. Figure 1 compares radiation for 25-degree enclosing walls and convection for large plane surfaces as given by McAdam's equations.[6] Figure 2 gives radiation for several other enclosing surface temperatures. The curves are useful in approximating the temperature rise under conditions near hot walls.

Solar Radiation

The radiant energy received from the sun has been the subject of many careful measurements.[8,9,10] It fluctuates about seven per cent due to variation in the distance of the sun and sun spots. The radiant energy from the sun as it would be measured by an observer at the earth's mean solar distance but outside our atmosphere, is called the "solar constant."

The mean of 692 determinations of the solar constant in the period from 1902 to 1912 gave a value of 1.94 gram-calories per (minute × centimeter square) or 0.87 watt per square inch.[11]

The intensity of radiation as measured at the earth's surface varies over a wide range, depending on the altitude, humidity, and cloudiness. The curves of figure 3 are plotted from values given in the Smithsonian Physical Tables[11] and give the intensity as a function of wave length for various altitudes and angles of the sun from the zenith. These curves apply to conditions of low humidity and no volcanic dust, so that they give practically maximum values of direct solar radiation.

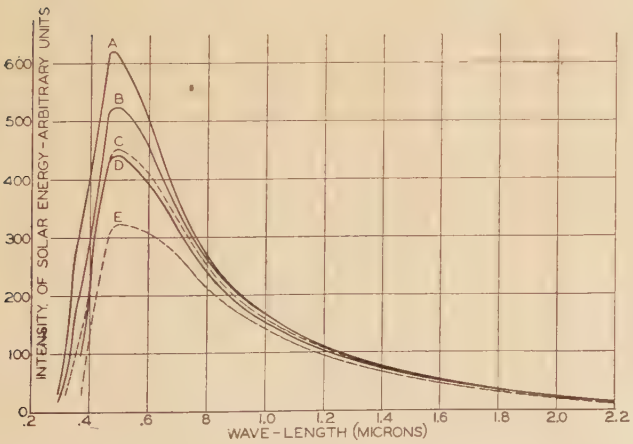


Figure 3. Intensity–wave length curves for direct solar radiation

A—Outside the earth's atmosphere
B—Mount Wilson—5,680-foot elevation, zero degree angle of sun from zenith
C—Mount Wilson—5,680-foot elevation, 60-degree angle of sun from zenith
D—Washington, D. C., 112-foot elevation, zero degree angle of sun from zenith
E—Washington, D. C., 112-foot elevation, 60-degree angle of sun from zenith

A large portion of the reduction in solar energy in passing through the atmosphere is due to scattering. Much of this scattered energy reaches the earth as "sky light." This has not been studied as extensively as the direct solar radiation. In general, the scattered radiation or sky light is increased as the direct solar radiation is decreased by a longer path through the atmosphere or by increased haziness. Abbot[12] gives a value of sky light on Flint Island (sea level) of 32 per cent of the direct radiation and for Mount Wilson 7 per cent of the direct radiation.

Taking 0.6 as a typical value of direct radiation at sea level, 32 per cent of 0.6 gives 0.19 watt per square inch as sky light. For Mount Wilson 7 per cent of 0.74 gives 0.05 watt per square inch as sky light. The total radiation received by a horizontal surface with the sun at zenith would then be $0.6+0.19=0.79$ for Flint Island and $0.74+0.05=0.79$ for Mount Wilson. These meager data would seem to indicate that under favorable conditions a surface at sea level may receive nearly as much total energy as at high altitude, and that this value may be as high as 0.8 watt per square inch. Houghten, Blackshaw, Pugh, and McDermott[1] give values of solar radiation

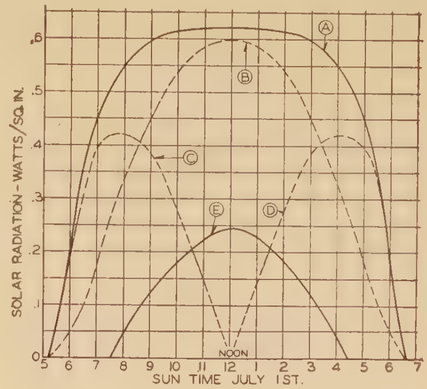


Figure 4. Solar radiation July 1 at Pittsburgh, Pa.

A—Surface normal to sun
B—Horizontal surface
C—East wall
D—West wall
E—South wall

* Watts, inches, and degrees centigrade are generally used in this paper because they are believed to be the most convenient units for the electrical engineer. To convert watts per square inch to Btu per (hour × square feet) multiply by 493; to convert to gram calories per (second × square centimeters) multiply by 0.037.

as measured at the United States Weather Bureau station in Pittsburgh, Pa. Figure 4 gives their values. Their maximum value of radiation is 0.63 watt per square inch. From the data available, the writer considers 0.75 watt per square inch as the typical maximum value of solar radiation (that is, 20 per cent greater than that given by figure 4).

Effect of Solar Radiation on the Temperature of Apparatus

As has been mentioned, most devices having forced air circulation or water cooling, will have a high loss per unit

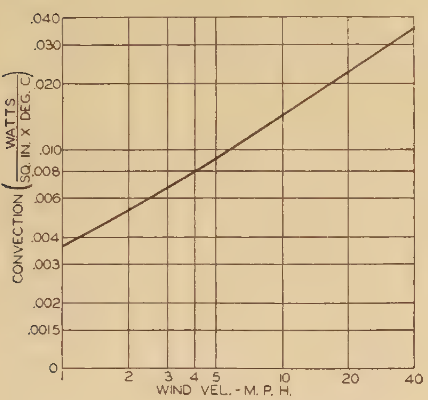


Figure 5. Convection from six-inch-diameter cylinder as affected by air flow perpendicular to axis of cylinder

of external projected area exposed to the sun. The heat received from the sun is, therefore, small as compared to the normal losses and has a negligible effect on the temperature rise. Such cases will not be considered further.

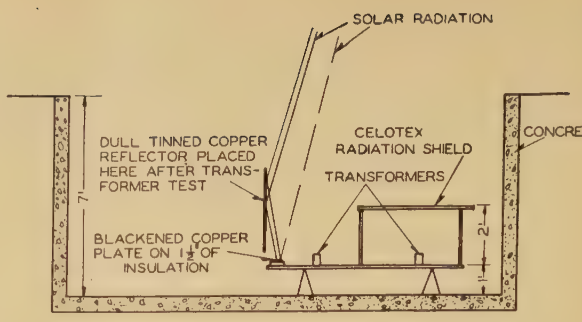
The heat received by apparatus exposed to the sun can be estimated from data on solar radiation. If all parts of the device can be assumed to be at the same temperature, and if the watts lost and temperature rise under test conditions are known, the watts dissipated per degree rise can be calculated. The additional rise due to radiation from the sun can be estimated.

However, under service conditions, several factors tend to reduce the temperature below that which would be obtained in this way.

1. Large apparatus cooled by natural convection and radiation approaches its final temperature slowly so that the solar radiation will be decreasing before the apparatus reaches its maximum temperature.

2. Most locations exposed to the sun will likewise be exposed to wind which will give a greater loss per degree by convection than that obtained in the test floor.

Figure 6. Diagram of apparatus for measuring temperature rise due to solar radiation



3. The sky is very seldom cloudless, so that the maximum value of solar radiation is seldom obtained continuously.

Apparatus exposed to the sun receives direct and scattered radiation and radiates to the sky. To be strictly accurate in estimating the radiation from apparatus out of doors, the effective temperature of the sky should be used. However, calculations indicate that for apparatus with a surface rise of 50 degrees centigrade or less, such refinements are not justified by the accuracy of our knowledge of scattered radiation and effective temperature of the sky. The term "sky light" has been applied to the net radiant energy received by a black surface exposed to the sky, taking as zero the condition when the black surface is covered by a radiation shield at ambient temperature. Sky light is, therefore, the difference between the scattered solar radiation falling on the measuring surface and the additional heat radiated from this surface due to the fact that it is exposed to the sky rather than to a surface at ambient temperature. Therefore, in this paper the additional temperature rise of apparatus due to solar radiation will be calculated on the assumption that the apparatus receives both direct solar radiation and sky light, and that the apparatus dissipates its heat as though it were radiating to surfaces at ambient temperature.

Figure 5 is a curve of convection as affected by wind velocity. This curve was plotted from a dimensionless curve given by McAdams.[7] From this curve it is evident that a wind velocity of one mile per hour is sufficient to give a noticeable increase as compared to natural convection in still air. A wind velocity of ten miles per hour gives a convection coefficient of 0.014 watt per (square inch × centigrade degrees). At 40-degrees centigrade rise this gives 0.56 watt per square inch, which is 4.3 times the loss by natural convection. Appendix I considers a simplified case of apparatus exposed to sun and wind simultaneously, showing that a wind velocity of four miles per hour is sufficient to compensate for the heat received from the noonday sun.

Another method of reducing the temperature rise due to solar radiation is to use a paint which reflects much of the short-wave-length radiation, but acts as a good radiator for long wave lengths. White paint may absorb only 25 per cent of solar radiation but 95 per cent of long wave lengths. There would be few locations where a clean white surface could be maintained, but a gray paint showing an appreciable gain might be practical. Metallic pigments as in aluminum paint give a high reflectivity for all wave lengths. This reduces the solar radiation absorbed, but also reduces the dissipation of heat by radiation so that the device will usually operate at a higher temperature than if painted black. Montsinger[13] has discussed this question, and has given several typical curves showing the temperature rise of transformers under service conditions. The wind velocity was not reported, so that his values cannot be used to predict the temperature which would occur under other wind conditions.

Test Results

Under many conditions there will be sufficient wind so that the increased convection will compensate for the heat received from the sun. Occasionally there are periods of calm, or apparatus may be mounted in locations where it is shielded from the wind by buildings.

Tests were made to demonstrate the temperature rise which may occur under certain conditions due to solar radiation. Two small (100-watt) transformers were used. To determine any differences in manufacture or position of inserted thermocouples, tests were first run in the laboratory. The temperature rise obtained in the first test is plotted in curves $A1$, $B1$, and $AB2$ of figure 7. This shows that the iron temperature of both transformers was the same, but that the copper of transformer A ran about 2 degrees warmer than that of transformer B. To be certain that both were loaded

equally, the primaries were operated in parallel and the secondaries in series supplying a common lamp load.

To obtain results not influenced by clouds, the field tests were made in Colorado at 38 degrees latitude and at an elevation of 4,200 feet. The first test was made with the transformers supported about one foot above the ground and in a location shielded from the wind by a small building. Transformer *B* was exposed to the sun, while transformer *A* was shaded by a piece of Celotex four feet by four feet supported about two feet above the transformer. The arrangement was similar to that shown in figure 6, except that the test was made on level ground instead of in a pit. The results of this test are shown as curves *A*3 and *B*3 of figure 7. While an attempt had been made to locate the test where it would be shielded from the wind, this was not entirely successful. Especially toward the end of the test, gusts of wind would occasionally give anemometer readings of 75 feet per minute near the transformers. It is believed that the drop in temperature near the end of the test was caused by these gusts of wind. Under these conditions the copper of transformer *B* which was exposed to the sun operated at 17 degrees centigrade greater rise than that of transformer *A* which was shaded, although in the laboratory the copper of transformer *A* had been 2 degrees warmer. The difference due to solar radiation was, then, 19 degrees centigrade.

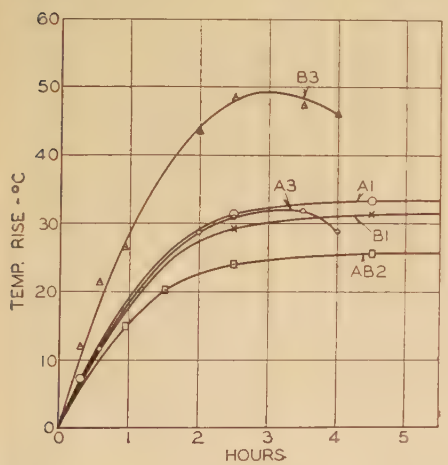


Figure 7. Time–temperature rise curves of small transformers

*A*1—Copper temperature of transformer *A* as tested in laboratory

*B*1—Copper temperature of transformer *B* as tested in laboratory

*AB*2—Iron temperature of transformers *A* and *B* as tested in laboratory

*B*3—Copper temperature of transformer *B* exposed to the sun

*A*3—Copper temperature of transformer *A* shaded

To eliminate the effect of the wind, another test was made in a pit 7 feet deep by 15 feet wide with concrete walls. This test arrangement is shown in figure 6. This time transformer *A* was exposed to the sun and transformer *B* was shaded. As would be expected in a location so well shielded from the wind, the ambient temperature rose considerably. For this reason actual temperatures are plotted rather than temperature rise in figure 8. In this test at the end of $2^1/_2$ hours the copper of transformer *A* was 22 degrees warmer than that of transformer *B*. Correcting for the 2-degree difference in the laboratory test, the rise due to radiation would be 20 degrees centigrade. The effect of solar radiation on iron temperatures was to give an additional rise of $20^1/_2$ degrees centigrade. An approximate calculation of temperature for this case is given in the appendix.

To illustrate one unusual condition, a piece of blackened sheet copper was mounted on $1^1/_2$ inches of thermal insulation (wood-pulp packing material). In this way the loss from the back of the sheet metal was small and the area for dissipating heat by convection was the same as the area exposed to radiation. With an ambient of 40 degrees centigrade the sheet metal attained a temperature of 90 degrees centigrade. To illustrate the effect of possible reflections, a piece of dull tinned copper was set up as a reflector as shown in figure 6. This increased the temperature of the blackened metal to 109 degrees centigrade. Or course, many other special tests could be made showing still higher local temperatures. Apparatus under a glass cover gets very hot because most glasses transmit solar radiation efficiently, but are opaque to long wave lengths, so that apparatus under glass receives solar radiation but cannot be cooled by radiation through the glass. Almost everyone is familiar with the use of a lens or parabolic mirror to produce fire, which is an extreme example of high temperature resulting from solar radiation.

Summary

In apparatus with a smooth exterior surface and without fans or liquid cooling, radiation to surrounding objects is usually more important than convection. In this case, the surface temperature of surrounding objects may be more important than the air temperature.

Solar radiation on clear days may be as high as 0.8 watt per square inch of surface normal to the sun.

The effect of solar radiation on the temperature rise of apparatus with forced air circulation or water cooling is generally negligible.

If apparatus cooled only by natural convection and radiation from a smooth surface is exposed to the sun but shielded from the wind, additional temperature rise may be of the order of 20 degrees centigrade. However, a wind velocity of a few miles per hour can compensate for the solar radiation. The effect of solar radiation can be decreased by white or gray paint.

High local temperatures can result from unusual conditions, a common example being an object with a glass cover. An extreme example is the high temperature at the focus of a parabolic mirror or lens.

Appendix

Approximate calculations are given for two smooth-exterior, self-cooled devices showing the additional temperature rise resulting from exposure to the sun in still air, and the effect of a slight wind on the temperature rise.

A. Calculations for 100-Watt Transformers Used in Tests

Under laboratory conditions the transformer case operated at an average temperature rise of 21 degrees centigrade. The total surface area was 81 square inches. Using the curves of figure 1 in approximating the heat dissipated from the case gives, in watts per square inch,

Convection loss	0.055
Radiation (e=0.95), 0.092×0.95=	0.087
Loss by radiation and convection	0.142

0.142×81 = 11.5 watts total heat dissipated, which compares with measured losses of 12 watts

When operating in the sun, the total solar radiation from the curves of figure 4 give 13.8 watts at 9 a.m. This value is obtained by multiplying the projected horizontal area by the value per square inch for a horizontal surface from curve *B* of figure 4; the east area by the value given by curve *C*, etc. At 10 a.m., the radiation was 14.2 watts; at 11:00, 13.3 watts, and at noon, 11.6 watts. Averaging these values gives 13.3 watts as the average heat from the sun, which would be received by a perfect black body. The value of emissivity was assumed to be 0.95. The curves of figure 4 were obtained from the weather-bureau station in Pittsburgh, Pa. From the data available, the values for Colorado are probably 20 per cent higher.

Correcting the above average in this way gives

13.3×0.95×1.2 = 15 watts

as the estimated average solar radiation.

Adding this to the 12 watts electrical losses gives 27 watts, or 0.33 watt per square inch. By trial and error, using figures 1 and 2, we find that 40-degrees centigrade rise gives, in watts per square inch,

Radiation (40-degree surroundings) $0.23 \times 0.95 =$	0.205
Convection loss	0.126
Total	0.331

This gives an additional surface rise of $40-21=19$ degrees centigrade. The drop from copper and iron to the surface is not changed, so that all temperature rises should be 19 degrees higher than in the shade, which compares with $20^1/_2$ degrees centigrade in the test values given by figures 7 and 8.

B. Effect of Wind

To illustrate the effect of the wind, assume that some device (for example, a transformer) in a cylindrical case six inches diameter by ten inches high is mounted on a pole. Assume the case is smooth and at a uniform temperature. Calculating the solar heat input by considering as before the horizontal, east, south, and west projected areas and the corresponding values of radiation, gives an average heat input from 9 a.m. to 12 noon of 39.5 watts or

$\frac{39.5}{244}=0.162$ watt per square inch of total surface

Assuming that the normal surface rise is 30 degrees centigrade above an ambient of 25 degrees centigrade gives a heat dissipation of

Convection loss 0.085 watt per sq. in.
Radiation $0.135 \times 0.95 =$ 0.128 watt per sq. in.

0.213 watt per sq. in.

0.213×244 square inches $=52$ watts normal dissipation

$0.213+0.162$ sun effect $=0.375$ watt per square inch

to be dissipated when exposed to the sun. By trial and error from figure 1

47 degrees centigrade rise gives
Convection loss 0.155 watt per sq. in.
Radiation 0.23×0.95 0.22

0.375 watt per sq. in.

We would then expect this device to operate at 17 degrees centigrade additional rise if exposed to the sun with no wind.

A wind of four miles per hour gives from figure 5 a heat dissipation of 0.008 watt per (square inch $\times$ centigrade degrees). At 30-degrees centigrade rise, this gives

0.24 watt per square inch convection loss
$0.135 \times 0.95 = 0.13$ watt per square inch radiation
$0.24+0.13=0.37$ total

In other words, a wind of four miles per hour would increase the convection by an amount equal to the heat received as solar radiation, so that the temperature rise in the sun would be the same as on the test floor.

A wind of ten miles per hour would give a convection coefficient of 0.014 watt per

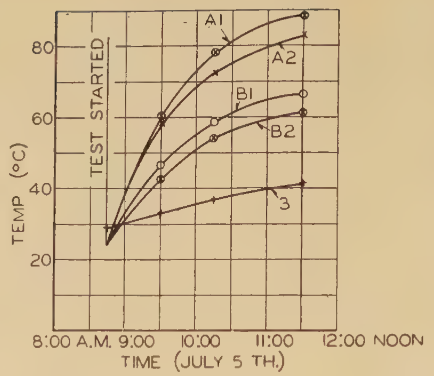


Figure 8. Time–temperature curves of transformers shielded from the wind

*A*1—Copper temperature of transformer *A* (exposed to sun)

*B*1—Copper temperature of transformer *B* (shaded)

*A*2—Iron temperature of transformer *A*

*B*2—Iron temperature of transformer *B*

3—Ambient air temperature

(square inch $\times$ centigrade degrees). At 21 degrees centigrade rise this gives

Convection loss $(0.014 \times 21) =$ 0.294 watt per square inch
Radiation $0.095 \times 0.95 =$ 0.09 watt per square inch

0.384 watt per square inch

Therefore, a wind of ten miles per hour would dissipate the heat at 21 degrees centigrade rise, or 9 degrees centigrade below normal.

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Discussion

M. F. Beavers (General Electric Company, Pittsfield, Mass.): This paper presents some very interesting test data on the effect of solar radiation and wind on the thermal characteristics of small transformers compared to the characteristics under laboratory conditions.

Mr. Penney concludes among other things in his summary that "If apparatus cooled only by natural convection and radiation from a smooth surface is exposed to sun but shielded from the wind, additional temperature rise may be of the order of 20 degrees centigrade. . . ."

This certainly should be a warning to avoid installing small transformers with smooth surfaces in a location shielded from the wind but exposed to the sun for the major part of the day. It is probable that a small percentage of installations fall into this class.

On the other hand, it should not be alarming to those who have made tests or obtained reports to the effect that the temperature rise over ambient of an ordinary oil-immersed pole-type distribution transformer, under actual service conditions, will run only five to ten degrees centigrade higher on a sunny day than on a cloudy day or during the night.

Therefore I would like to recall to your attention some statements in Mr. Penney's paper which, I believe, will tend to show better correlation with previous tests on pole-type distribution transformers under actual service conditions.

Referring to the additional rise due to exposure to the sun but shielded from the wind, Mr. Penney points out that ". . . under service conditions, several factors tend to reduce the temperature below that which would be obtained in this way.

"1. Large apparatus cooled by natural convection and radiation approaches its final temperature slowly so that the solar radiation will be decreasing before the apparatus reaches its maximum temperature.

"2. Most locations exposed to the sun will likewise be exposed to wind which will give a greater loss per degree by convection than that obtained in the test floor.

"3. The sky is very seldom cloudless, so that the maximum value of solar radiation is seldom obtained continuously."

Item number 13 in Mr. Penney's bibliography refers to an article by Montsinger and Wetherill entitled "Effect of Color of Tank on the Temperature of Self-Cooled Transformers Under Service Conditions" in which the results of various tests on distribution transformers located outdoors under normal weather conditions are given.

Table I

Color of Tank	(1) Min.	(1) Avg.*	(1) Max.	(2) Min.	(2) Avg.*	(2) Max.	(3) Min.	(3) Avg.*	(3) Max.
	Oil Temperature Rise—Deg C								
Black	4	6.9	11.5	8	10.8	15	20	24	29.5
Medium gray	4	7.16	10	10	12	16.5	20	23.4	29
Light gray	1.5	3.67	7.5	7	10.55	14	18	22.8	27

(1). Transformer without excitation or load (idle).
(2). Transformer with normal excitation only (no load).
(3). Transformer with normal excitation and normal load.
* Average temperature rise over a 24-hour period.

Figure 1 of the Montsinger-Wetherill paper shows a chart of oil temperature and ambient air temperature for a period of two days for four 5-kva transformers under excitation only (that is, no load). Two of the transformers were in black-painted tanks, one was white, and one was aluminum painted (tests were made in Pittsfield, Mass.).

In order to show the effect of the sun on the transformers in the black-painted tanks I analyzed the oil temperature rise over ambient air for the two-day period from August 12 to 14, 1909. The average minimum oil rise of 7 degrees centigrade occurred in the neighborhood of 4 a.m. to 8 a.m. and the maximum oil rise of 14 degrees centigrade occurred at 6 p.m. The additional rise due to the sun, then, is $14-7=7$ degrees centigrade.

With reference to the temperature of the transformers in the white and aluminum-painted tanks Montsinger states ". . . that the transformer with the black tank averages one to two degrees centigrade hotter than the one with the white tank. . . . The temperature of the aluminum-painted tank was as a rule between those of the black and white tanks."

Tests made on several 3-kva lighting transformers in August and September 1922, by Messrs. Moore and Moulton of the San Joaquin Light and Power Corporation are reported in this reference and are summarized in table I of this discussion.

An analysis of the data from which this summary was taken indicates that the maximum oil rise occurs in the vicinity of 6 to 8 p.m. and the minimum oil rise occurs during the early part of the morning with very little increase in rise before 10 a.m.

The additional temperature, then, due to the sun, is the difference between the minimum and maximum oil rises observed.

For the Moore-Moulton tests the maximum difference is 9.5 degrees centigrade, on the transformer in the black tank under normal load and excitation.

In regard to the benefits of the gray paint Moore and Moulton concluded that "We have reached the conclusion, after a very careful study of the results herein recorded, that any additional expenditure to procure a gray case instead of black would not be justified."

V. M. Montsinger (General Electric Company, Pittsfield, Mass.): I wish to discuss the curves given in figures 1 and 2 of Mr. Penney's paper. In my work I have used curves or equations quite similar to those used by the author. For example: I have used 36.8 for the constant in the radiation formula, and 0.95 for the emissivity factor e_1 for all surfaces painted with non-metallic or pigment paints.

The equation of curve C in figure 1 for loss of heat by convection from a large vertical surface appears to be, $W_c=1.265\times 10^{-3}\ \theta^{1.25}$, where W_c=watts per square inch and θ=temperature rise in degrees centigrade. I have used the same form of equation but with a constant of 1.4×10^{-3} which gives approximately ten per cent more loss by convection than curve C gives for the same temperature rise.

The curves in figure 1 show that the percentage of losses from a large vertical surface are approximately 60 per cent by radiation and 40 per cent by convection at 25 degrees centigrade. I have found approximately 55 per cent and 45 per cent respectively, the difference being due to the difference in the constants used in the convection formula. This ratio changes with room temperature, since loss of heat by radiation increases with increasing room temperatures, whereas loss by convection is practically unaffected by changes in room temperature. An easy rule to remember is that loss by radiation increases from 1.0 to 1.2 per cent for each degree increase in the room temperature. This is shown by the curves in figure 2. For example: for 60 degrees rise the ratio of the losses in a 100-degree room and a 25-degree room is $(0.57/0.30):1.9$. That is, the loss is 90 per cent more in a 100-degree room than in a 25-degree room. 90 per cent divided by 75 degrees gives 1.2 per cent increase per degree. For 80 degrees rise the difference between the 40 and 100-degree curves is one per cent per degree. The average value is approximately 1.1 per cent.

For limited temperature rises—up to about 75 degrees—it is possible to approximate closely loss of heat by radiation at various room temperatures by a simple logarithmic equation, as is shown on page 272 of the book on "Transformer Engineering". The equation is:

$$W_r=1.84\times10^{-3}\theta^{1.19}E\left(1+\frac{1.1\theta_a}{100}\right)$$

where

W_r=watts per square inch
θ=temperature rise degrees centigrade
E=emissivity factor
θ_a=room temperature degrees centigrade

Referring again to loss of heat by convection, it should be kept in mind that the constants mentioned before apply only to large vertical surfaces of approximately two feet height and more. For short heights, the constant increases. Some investigators state that the loss varies inversely as the height raised to the one-fourth power. For example: if the loss is unity for a 24-inch height, for a 2.4-inch height the loss would be $(24/2.4)^{1/4}=1.78$ or 78 per cent more watts per square inch for the same temperature rise. I would like to ask Mr. Penney if he took the height of his 100-watt transformer into consideration when evaluating the ratio of losses by radiation and convection. If not, I am inclined to believe that the effect of the short vertical surface of the 100-watt transformer on the loss by convection was much more than the effect of the low wind velocity.

Referring to my paper—reference 13—as Mr. Penney surmises no record was made of the wind velocity when the field tests were made. The conditions under which the several tests were made correspond to those under which transformers operate in service. As all the tests indicated that the effect of the color of the tank on the relative temperature rise was quite small, two degrees centigrade at the most, it is felt that the conclusions drawn were sound, namely, that the question of the kind of paint used on distribution and power transformers exposed to the sun's rays, is one of appearance and durability only.

R. E. Hellmund (Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): Mr. Penney's paper gives some very important practical as well as theoretical information on the effects of radiated heat on apparatus. In addition to apparatus intended for outdoor installation, apparatus designed for indoor use is frequently installed outdoors in enclosures of some kind or other. From Mr. Penney's paper it would seem that if these enclosures are ventilated, the sun radiation will have little influence. On the other hand, if the enclosures are not ventilated and if the surface of the enclosure is much larger than the surface of the apparatus enclosed, conditions might be different from those of the transformer discussed in the paper. It would be interesting if Mr. Penney could give in his closing discussion some data regarding installations of this kind.

R. E. Hellmund and **F. R. Benedict** (nonmember; both of Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): Mr. Penney's paper discusses two factors, namely, sun radiation and wind, as affecting temperature conditions of electrical apparatus installed outdoors. It may therefore be appropriate to give some data which have recently become available on outdoor temperatures. In the paper entitled "Temperature Survey of the United States," by J. J. Smith and H. W. Tenney, which was presented at the 1939 AIEE summer convention, some valuable information was given on ambient outdoor temperatures in the United States. It is now generally conceded that the life of insulation is a function of both temperature and time during which certain high temperatures prevail. It is also well known that temperature variations below a certain

safe temperature have little influence upon the deterioration of insulation. In view of this, the electrical engineer is interested principally in ambient-temperature conditions in excess of certain values and the time during which they prevail. The information of this nature given by Smith and Tenney covered seven selected typical stations for the period 1934 to 1938 inclusive, and included curves for the average number of hours per year and the average number of hours per day versus the average number of days per year during which the ambient temperature exceeded 90 degrees Fahrenheit. The paper also gave information for three selected stations for the period 1934 to 1939 inclusive, using 105 degrees Fahrenheit as a basis. These data were prepared from records of the United States Weather Bureau.

It is naturally desirable to have similar data from a larger number of stations, and such data have been made available in tables published in *Heating and Ventilating*, March 1939, under the subject "Number of Hours Per Year of High Dry-Bulb Temperatures." These tables give an analysis of 41 well selected and distributed stations. Three tables are shown, as follows:

Table 1. The maximum number of hours in a year that dry-bulb temperature exceeds 85, 90, 95, 100, 105, 110, and 115 degrees Fahrenheit. Maximum in any year from 1932 to 1937 inclusive.

Table 2. The average number of hours per year the dry-bulb temperature exceeds 85, 90, 95, 100, 105, 110, and 115 degrees Fahrenheit. Average for the years 1932 to 1937 inclusive.

Table 3. The minimum number of hours in a year that dry-bulb temperatures exceed 85, 90, 95, 100, 105, 110, and 115 degrees Fahrenheit for the years 1932 to 1937 inclusive.

From these data the number of hours the ambient temperature exceeds 30, 35, 40, and 45 degrees centigrade can be obtained (85F=29.4C; 95F=35C; 105F=40.5C; 115F=46.1C).

For our problem the data in table 2 are most pertinent because they cover averages for a period of six years. In a study of the deterioration of insulation we are interested not so much in an individual or maximum-temperature year, but in what happens during the entire life of the equipment. A 6-year period gives a pretty good idea of this, as any variations that may exist between a 6- and a 10- or 20-year period are negligible for the problem at hand.

Referring to table 2, we find that the average number of hours per year during which the temperature exceeds 35 and 45 degrees centigrade for the station having the maximum average number of hours above the given temperature is as follows:

Deg C	Hours	Station
30	1,084	Dallas, Tex.
35	292	Topeka, Kans.
40	37	Topeka, Kans.
45	0	

Expressed in percentage of total hours per year (8,760 hours), this leads to table *A* in figure 1 of this discussion.

As will be seen, the maximum hours for a given temperature do not all occur at the same station and thus no individual piece of apparatus is exposed to conditions quite as severe as those indicated in the table. It is therefore quite safe to state that, for our problem, the figures in table *A* represent the "maximum climatic ambient temperatures" in the United States. It may well be contended that the use of the maximum ambient conditions met by all electrical apparatus will lead to poor economy in the application of the large majority of apparatus. Reference to table 2, *Heating and Ventilating*, March 1939 indicates that the stations which are of high average are localized in Texas, Oklahoma, Kansas, Arkansas, and Louisiana. If stations in these areas are eliminated, the station with the maximum average number of hours at the given temperatures will then be as follows:

Deg C	Hours	Station
30	892	Kansas City, Mo.
35	248	Kansas City, Mo.
40	32	Kansas City, Mo.
45	0	

In considering the elimination of some stations or areas, the number of motors and horsepower installed in the various states in which the high-average stations were located, was taken into account. The paper by Smith and Tenney gives sufficient data to show that the elimination of Texas, Oklahoma, Kansas, Arkansas, and Louisiana involves only 3.05 per cent of the total number of motors and 3.9 per cent of the total horsepower installed (probably less than 5 per cent of all electrical apparatus). On the basis of an 8,760-hour year, the predominant climatic ambients for the areas in which over 95 per cent of all electrical apparatus is installed would then be as shown in table *B*, figure 1.

Stated in another way, it would be expected that the ambient temperature would be above 30 degrees centigrade ten per cent of the time or less; above 35 degrees centigrade three per cent of the time or less; above 40 degrees centigrade 0.5 per cent of the time or less; and above 45 degrees centigrade such a small part of the time that for all practical purposes it can be considered as zero.

It may be of interest to consider only the essential industrial areas of the country. This can be done by excluding North Carolina, Tennessee, and the states south thereof, the southwest corner of Illinois, the states of Iowa and Nebraska and those south thereof, the states Arizona, Nevada, Utah, and New Mexico, and the southeast corner of California. We then find conditions as shown in table *C*, figure 1, for the areas included.

As a matter of course, the values in these tables apply also for any well-ventilated indoor areas where the indoor temperature is about the same as the outdoor. In indoor areas not so well ventilated and in which the electrical and other heat-generating apparatus is small compared with the space available, conditions should be even more favorable. On the other hand, in poorly ventilated indoor areas having a relatively large amount of heat-generating electrical apparatus and other heat-producing devices such as turbines, steam pipes, etc., conditions may be less favorable. Unfortunately, very few reliable data are available for such cases. There may also be indoor installations, especially in factory buildings with glass roofs, where the heat from sun radiation may raise the indoor temperature above the outdoor. Since these last two conditions may apply to an appreciable percentage of electrical apparatus, the compilation of data for installations of this nature seems desirable. However, the ambient temperature conditions given in this discussion, together with the information in Mr. Penney's paper and the Smith and Tenney paper should be of value in the application of electrical ap-

Figure 1

Circles indicate weather-bureau stations

Table *A*. Climatic Ambient for the Country on the Basis of Maximum-Hour Station

Temperature Below (Deg C)	Per Cent of Time
30	88
35	97
40	99.5
45	100

Table *B*. Climatic Ambient for the Country After Eliminating Stations Below the Solid Line

Temperature Below (Deg C)	Per Cent of Time
30	90
35	97
40	99.5
45	100

Table *C*. Climatic Ambient for the Country After Eliminating Stations Below the Dotted Line

Temperature Below (Deg C)	Per Cent of Time
30	95
35	99
40	99.5
45	100

Phase Occurrence of Arc-Backs in High-Current Mercury-Arc Rectifiers

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THE phenomenon of arc-back in mercury-arc rectifiers is the major factor in determining present-day designs. To keep the frequency of occurrence of arc-back sufficiently low, the anodes are set at a sufficient distance from the cathode, shields, baffles, and grids are interposed, and cooling water temperatures are kept in a rather narrow range. These practically successful means for overcoming arc-backs were developed largely empirically as the cause and nature of arc-back is still little understood.

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The authors wish to thank Doctor Joseph Slepian, who proposed collecting and publishing the data of this paper, and who is responsible for some of the suggestions in interpretation of the results.

1. For all numbered references, see list at end of paper.

In the normal operation of rectifiers, a transient small inverse current flows to each anode just after its voltage polarity reverses at the end of each normal current-conducting period. This inverse current is a maximum just after transition from the normal conducting to normal insulating state of the anode, and decreases rapidly to a small fraction of its initial value in less than ten electrical degrees, under usual operating conditions. The inverse current is believed to consist of positive ions reaching the anode from the rapidly disappearing residual ionization left before the anode in the preceding conduction period. Most investigators express a belief in a strong causal relationship between this inverse current and the arc-back frequency. The fact that the means mentioned in the preceding paragraph for reducing arc-back frequency also reduce greatly the inverse current seems strongly to support this view. Prince and Vogdes,[1] however, state that "if there is any connection between arc-back and the inverse current, it is probably rather remote."

Little is known as to where in the alternating cycle arc-back occurs. If the

Table I. Arc-Back Data for Rectifiers Tested

Rectifier Tested	Load Amperes	Load Volts	Point on Inverse Cycle at Which Arc-Back Occurred*
Six-phase ignitron	1,250	300	T
	1,250	300	T
	1,250	300	T
	1,250	300	T
	1,250	300	T
	1,250	300	T
	1,875	300	T
	1,875	300	T
	1,875	300	T+26 deg
	1,875	300	T
Six-phase multianode rectifier	2,400	600	T
	3,750	600	T
	3,750	600	T+37 deg
Six-phase ignition	1,250	600	T+170 deg and T+36 deg
	1,250	600	T+68 deg
	1,250	600	T+47 deg
	1,250	600	T+26.6 deg
	1,250	600	T+20 deg
Three-phase ignitron	400	600	T+13 deg
Six-phase ignitron	3,000	300	T+20 deg
	2,500	300	T+27 deg
	2,500	300	T
	2,500	300	T+16 deg
	2,500	300	T+6.5 deg
	2,500	300	T
Six-phase ignitron	1,000	600	T
	1,000	600	T+30 deg
Six-phase ignitron	2,500	600	T
	2,500	600	T
	2,500	600	T
	1,700	600	T
	1,700	600	T+22 deg
Six-phase ignitron	2,500	600	T
	2,500	600	T
	3,750	600	T
	2,500	600	T+23 deg
	2,500	600	T
	2,500	600	T
	6,000	600	T+53 deg
	6,000	600	T+79 deg
	2,500	600	T
	3,750	600	T+80 deg
	3,750	600	T
	7,500	600	T+93.5 deg
	7,500	600	T
	7,500	600	T
	5,000	600	T+128 deg
	5,000	600	T
	7,500	600	T
	7,500	600	T
	5,500	600	T+36 deg
	6,000	600	T
	2,500	600	T
	2,500	600	T
Single-phase full-wave ignitron	400	600	T
	400	600	T+85 deg
	400	600	T
	300	600	T
	600	600	T+76 deg
		600	T
	200	600	T+90 deg
	600	600	T+38.5 deg
	600	600	T
	400	600	T
		600	T
	800	600	T+106 deg
	800	600	T+56 deg
	800	600	T+82 deg
	200	600	T+36 deg
	200	600	T+23 deg
	200	600	T+77 deg
	800	600	T+93 deg
	800	600	T+54 deg
	800	600	T+127 deg

*T = Transition.

paratus, particularly transformers, the greater number of which are outdoors or in well-ventilated areas.

G. W. Penney: Natural convection depends on low-velocity air movements and therefore varies with the shape and size of the surface, type of ventilation in the room, and similar factors which are not normally closely controlled, so that rather large variations are to be expected between results obtained under various conditions. W. H. McAdams in his book on "Heat Transmission"[5] has compiled a good summary of available data. The curves of figure 1 are believed to represent average conditions for large objects.

As Mr. Montsinger mentions, natural convection for small objects is frequently assumed to vary inversely as the one-fourth power of the height, but this simplification usually requires some adjustment of constants. McAdams (page 244) gives a curve showing the variation of convection with height of cylinder which would give convection as varying inversely with a fractional power of the height up to 10 inches and then gradually changing to a constant value for heights over 18 inches. In reply to Mr. Montsinger's question as to the value used for the 100-watt transformer mentioned in the paper, if we use the formula for convection as a function of height as given by McAdams on page 245, equation 32, a value of 12 per cent greater than that given by figure 1 would be obtained. However, the transformer was tested sitting on a wooden platform as shown in figure 6. This platform somewhat obstructed the natural convection so that it was believed that the curves of figure 1 probably came very close to the actual condition.

Heat dissipation due to wind velocity depends on the size of the object and is also commonly approximated as varying inversely as the one-fourth power of the size of the object cooled so that the relative effect of the wind tends to be independent of the size of the object cooled.

Mr. Hellmund asked as to the effect of mounting apparatus in small outdoor enclosures, these enclosures being exposed to the sun. If the enclosure is not ventilated and if its temperature could be assumed to be uniform, the approximate methods suggested in the paper could be used to estimate the effect of the sun. Such a calculation would give an idea of the order of magnitude of the sun effect. However, the temperature throughout the case will not be uniform, and the sources of heat will be irregularly located so that tests should be made if exact figures are needed. A number of tests under typical operating conditions would be desirable.

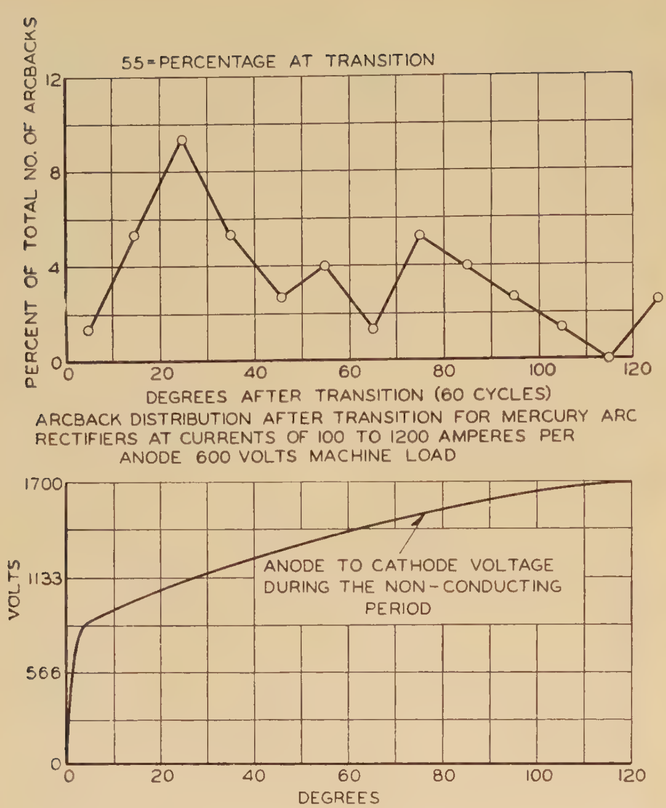

Figure 1 (above). Arc-back distribution and inverse voltage of a mercury-arc rectifier

Figure 2a. Oscillogram of an arc-back which occurred at transition

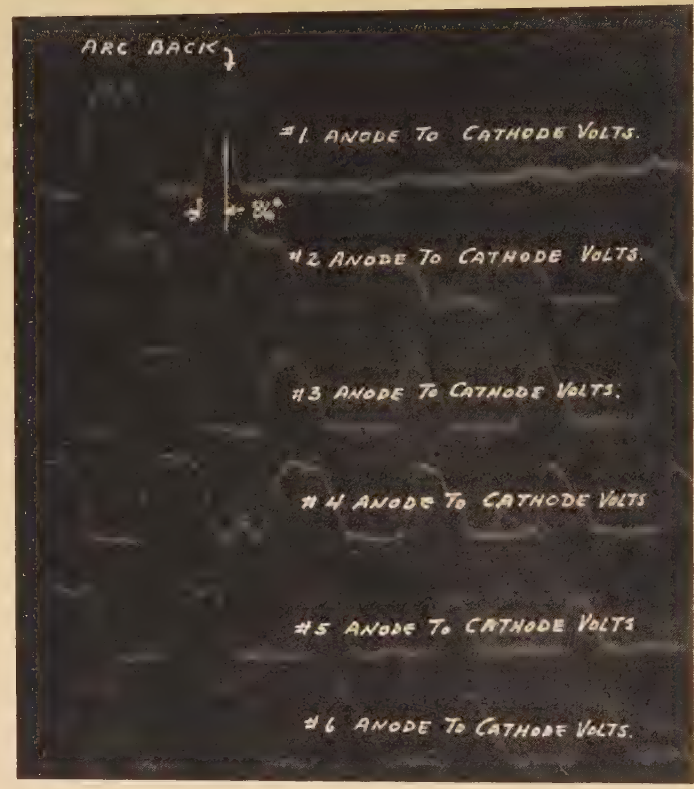

Figure 2b. Oscillogram of an arc-back which occurred 86 degrees after transition

inverse current is the controlling cause, then all arc-backs should occur immediately after transition, since under normal operating conditions for low-voltage rectifiers, there is considerable inverse current only just after transition. Actually the belief is quite widespread that arc-backs occur almost entirely at transition. Prince and Vogdes,[2] however, give a contrary viewpoint, and describe experiments with a tube in which quite definitely the arc-backs did not take place at transition. However, the tube used in their experiments was very special, so that it might still be believed that in practical low-voltage rectifiers, arc-backs occur only at transition.

It is difficult to determine the time of occurrence of arc-backs by usual oscillographic means with rectifiers operating under normal conditions, because of their completely random and infrequent occurrences. However, the development of the "memnoscope"[3] has solved these difficulties so that there has now accumulated a considerable number of oscillographic records which permit a direct determination of the time of occurrence of arc-backs in practically operating rectifiers. These records indicate that arc-backs occur frequently throughout the whole inverse period.

Table II. Per Cent of Arc-Backs at Transition for Each Rectifier Unit

Rectifier Tested	Number of Arc-Backs Observed	Per Cent at Transition
Six-phase ignitron, 300 volts	10	90
Six-phase multianode tank rectifier, 600 volts	3	67
Six-phase ignitron, 600 volts	5	20
Three-phase ignitron, 600 volts	1	0
Six-phase ignitron, 300 volts	6	33
Six-phase ignitron, 600 volts	2	50
Six-phase ignitron, 600 volts	5	80
Six-phase ignitron, 600 volts	22	66
Single-phase full-wave ignitron, 600 volts	20	35

Test Conditions and Procedure

All the oscillograms were taken on the test floor or in the laboratory, on commercial 300- and 600-volt rectifiers feeding a d-c motor. Currents ranged from 100 to 1,250 amperes per anode with zero ignition angle.

Anode to cathode voltages of all the anodes of a rectifier under observation were brought to memnoscopes whose outputs were passed through the elements of a magnetic oscillograph with continuously rotating cylindrical film. On occurrence of an arc-back, a reverse-current relay opened the oscillograph shutter, and a photographic record was thus obtained of the anode to cathode voltages preceding, during and after the arc-back. From these oscillographs the time of occurrence of the arc-back could be determined.

Results

Seventy-four oscillograms were obtained with arc-back occurrence times, as shown in table I. Two typical oscillograms are shown in figures 2*a* and 2*b*.

Forty arc-backs or 54 per cent occurred at transition. The remaining 34 or 46 per cent were distributed through the inverse period.

Station-Type Lightning-Arrester Performance Characteristics

AIEE LIGHTNING-ARRESTER SUBCOMMITTEE

THIS PAPER presents the results of additional work by the AIEE lightning arrester subcommittee and contains station-type-arrester performance values which may be expected of present-day commercial station-type arresters rated from 3 to 245 kv. The characteristics of line-type arresters were presented by the subcommittee in the May 1937 and November 1938 issues of ELECTRICAL ENGINEERING.

Table I includes station-arrester impulse gap breakdown values obtained from tests using the rate of voltage rise specified in the AIEE Standards for lightning arresters No. 28 or ASA Standards C-62; that is 100 kv per microsecond per 11.5 kv of arrester rating. To enable a more complete analysis of arrester performance, a complete curve (figure 1) of arrester gap breakdown voltage is included as a supplement to the tabulated values. This curve is plotted in per cent of the arrester's maximum permissible line-to-ground voltage rating, using the crest value of the voltage rating as the 100 per cent of reference point. The actual breakdown voltage for any arrester at any time T can be obtained by multiplying the crest value of the arrester's maximum permissible line to ground voltage rating by the percentage value indicated for any time T on the curve.

The 60-cycle spark potential of the arresters referred to in this report will not be less than 150 per cent of the arrester's maximum permissible line-to-ground voltage rating.

The table of arrester-performance values also includes the IR discharge voltage of the arrester valve element for currents of 1,500, 3,000, 5,000, 10,000, and 20,000 amperes, all of which are based on a current wave having a time to crest value of 10 microseconds and a time to 50 per cent of the crest value on the tail of the wave of 20 microseconds.

The lightning-arrester manufacturers have furnished the data from which the average characteristics of available station arresters are plotted and tabu-

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Personnel of AIEE lightning-arrester subcommittee: L. R. Ludwig, chairman; H. W. Collins, H. A. Dambly, J. M. Flanigen, I. W. Gross, Herman Halperin, J. C. McFarlin, J. R. North, H. L. Rorden, W. J. Rudge, A. H. Schirmer, H. K. Sels, L. G. Smith, H. R. Stewart, and E. R. Whitehead.

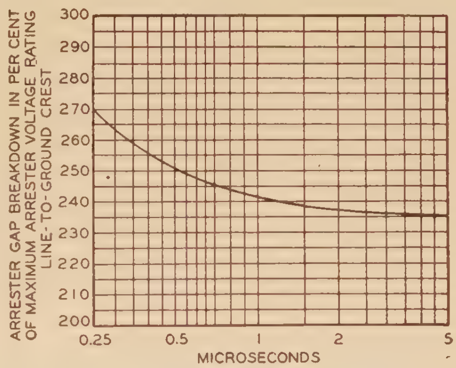

Figure 1. Impulse gap breakdown, tolerance ±20 per cent

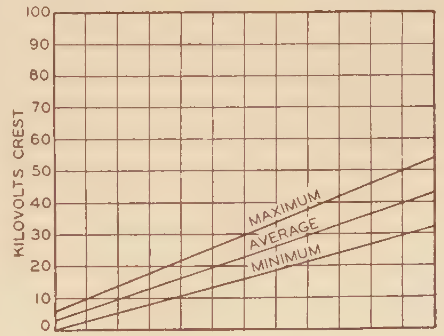

Figure 2. Impulse gap breakdown based on AIEE wave

The curve of figure 1 shows the distribution of these 34 arc-backs through the inverse period. Only one was observed at more than 130 degrees after transition. It occurred at 170 degrees and another anode arced back a few degrees later.

By direct experiment with a deck of cards it was found that the curve of figure 1 is not inconsistent with the hypothesis that the probability of arc-back is the same in each of the 10-degree intervals making up the 130 degrees. That is, 34 points placed at random in the 13 10-degree intervals gave distributions with as great a saw-tooth irregularity as shown in figure 1.

Discussion

The fact that only one arc-back was observed at more than 130 degrees later than transition may have been not because the later ones have a lower probability of occurrence, but rather to the method used for tripping the oscillograph shutter. On the six-phase rectifiers the oscillograph shutter was tripped by the reverse-current breaker, hence no record of arc-backs which clear without fault, if there are such arc-backs, was obtained.

There are not a sufficient number of arc-backs to obtain the true form of the distribution curve. About all that can be said definitely from the results obtained is that not all arc-backs have a probability of occurrence which is a strongly varying function of the instantaneous positive ion current density. The most that can be said in this direction would be that there are several types of arc-backs; and that one type, which constituted 54 per cent of the total, is occasioned by the momentary positive-ion current.

On the other hand, other possibilities will fit the above results. For example, we may postulate that arc-back causes occur at random throughout the cycle, but with effects lasting a cycle or more. In this case all causes which occur during the conducting period will produce their effect at transition and their number will depend on ratio of conducting to nonconducting period in the rectifier. If there is an equal probability for the whole inverse period, then for the double three-phase rectifier connection we should obtain $230°/360° = 63.8$ per cent of the arc-backs after transition and 36.2 per cent at transition. However, as can be seen from table II for the nine rectifiers tested, the fraction for each rectifier occurring at transition is very variable, which makes the possibility just discussed rather unlikely.

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3. A MEMORY ATTACHMENT FOR OSCILLOSCOPES, W. E. Pakala. AIEE TRANSACTIONS, volume 57, 1938, pages 682–4.

Table I. Industry Station-Type Arrester Characteristics

All *IR* Voltages on 10–20-Microsecond Current Wave; Kilovolts Crest

Kv*	Gap Breakdown on AIEE Rate			IR at 1,500 Amp.			IR at 3,000 Amp.			IR at 5,000 Amp.			IR at 10,000 Amp.			IR at 20,000 Amp.		
	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.
3	13	10	16	9	8	10	10	9	11	10	9	11	11	9	13	12	10	14
6	23	18	28	18	15	21	19	16	22	20	17	23	22	19	25	24	20	28
9	35	28	42	27	23	31	29	25	33	30	26	34	33	28	38	35	30	40
12	43	34	52	36	31	41	38	32	44	40	34	46	44	37	51	47	40	54
15	53	42	64	45	38	52	47	40	54	50	43	57	54	46	62	59	50	68
20	72	58	86	60	51	69	64	54	74	67	57	77	72	61	83	78	66	90
25	89	71	107	74	63	85	79	67	91	83	71	95	90	77	103	100	85	115
30	106	85	127	89	76	102	95	81	109	100	85	115	108	92	124	118	100	136
37	131	105	157	110	94	126	117	100	134	124	105	143	132	112	152	145	123	167
40	136	109	163	119	101	137	127	108	146	134	114	154	144	122	166	153	130	176
50	178	143	213	149	127	171	158	134	182	167	142	192	179	152	206	191	163	219
60	214	171	257	179	152	206	191	162	220	200	170	230	217	185	249	234	199	269
73	261	209	313	217	185	249	232	197	267	245	208	282	262	223	301	283	241	325
97	345	276	414	289	246	332	308	262	354	323	275	371	349	297	401	377	321	433
121	430	344	516	360	306	414	384	326	442	403	343	463	438	372	504	470	410	530
145	515	412	618	431	366	496	461	392	530	487	414	560	523	445	601	564	480	648
169	602	482	722	502	427	577	538	457	619	566	481	651	610	519	701	658	559	757
195	691	553	829	578	491	665	617	519	715	647	550	744	698	593	803	755	642	868
242	860	688	1,032	720	612	828	768	653	883	806	685	927	872	741	1,003	940	799	1,081

* Maximum permissible line-to-ground voltage rating.

lated. These values hold for new arresters and do not necessarily hold for the older types of arresters.

Tolerances are given to include the expected variation from the average values referred to above. The tolerance from the average value of gap breakdown is ±20 per cent and the tolerance from the average value of the *IR* discharge voltages is ±15 per cent.

By comparing the complete volt-time curve of the arrester with the complete volt-time characteristic of the insulation to be protected, a reasonable evaluation can be made of the margin of protection obtained.

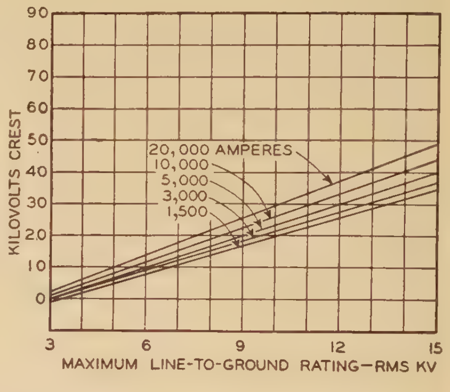

Figure 5. IR discharge voltage, 10–20-microsecond wave; tolerance ±15 per cent

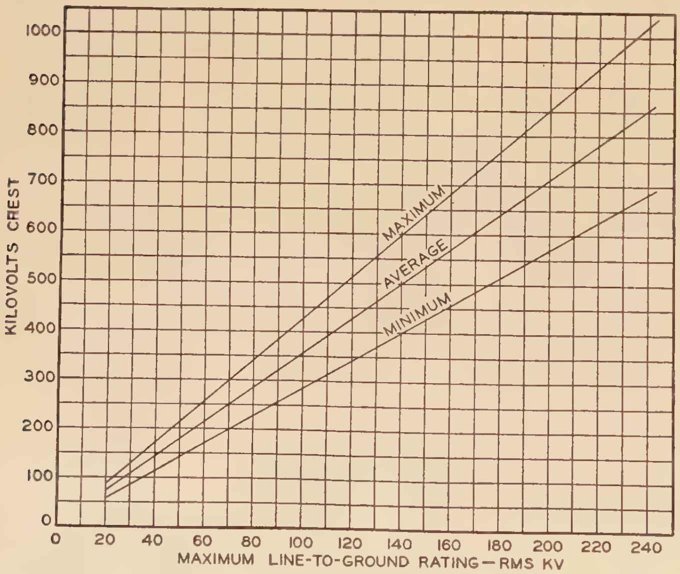

Figure 3. Impulse gap breakdown based on AIEE wave

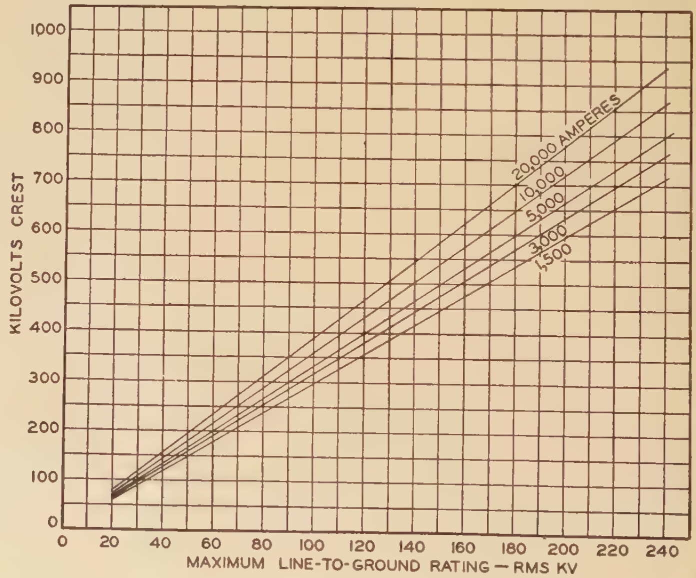

Figure 4. IR discharge voltage, 10–20-microsecond wave; tolerance ±15 per cent

The Measurement of Spot-Welding Current

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CURRENT is an essential factor in the complete specification of spot-welding conditions. Therefore, the need for the measurement of spot-welding currents arises, if optimum conditions determined in experimental laboratories are to be duplicated in production shops. Laboratory methods must be accurate and supplemented by facilities for ready calibration into secondary amperes. Shop methods must be convenient, reasonably accurate, and free from the possibility of accidental error. Shops find current measurement of great value in resetting welding machines for conditions which have previously been found satisfactory.

The problem is complicated by several factors, chief of which is the duration of current flow, which is commonly of the order of one-tenth second, but may be more or less. Another factor is the variable transient current produced by nonsynchronous closure of the welding circuit. A third factor is the wave shape of the welding current. Methods which depend upon the peak value of the current, or the rate of change of the current as it passes through its zero value, will be satisfactory for sinusoidal current waves. However, such methods will be of no value with wave shapes such as are produced by phase control of the firing of mercury-vapor tubes, or the wave shapes of stored-energy discharges.

The present paper includes brief descriptions of a variety of methods of current measurement, together with our evaluation of the methods, based upon experience in using them in spot-welding research programs, and upon the work of Mr. Muller in the preparation of his master's thesis. More recently a number of tests involving simultaneous determination by different methods have been made for the comparisons presented in this paper. The necessary calibrations to convert readings to secondary amperes were also performed. The magnetizing currents for the welding machine were determined through the range of the comparison tests to establish corrections for primary current readings.

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Methods of Current Measurement

Figure 1 diagrammatically illustrates various methods of measuring spot-welding current. The solid lines connecting the instruments to the welding circuit indicate the connection which we prefer to use. The dotted lines indicate alternate methods of connection. We shall discuss these methods individually in the following order:

1. Electromagnetic oscillograph with secondary shunt
2. Electromagnetic oscillograph with primary shunt
3. Current-crest meter
4. Cathode-ray oscillograph with primary shunt
5. Pointer-stop ammeter with primary clamp-on current transformer
6. Vacuum-tube voltmeter with secondary current transformer
7. Neon-tube meter with secondary toroid

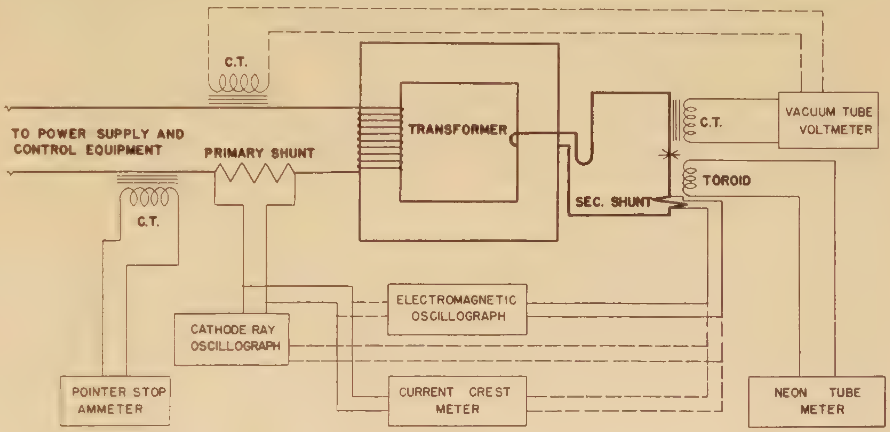

Figure 1. Various methods of measuring spot-welding currents

Electromagnetic Oscillograph—Secondary Shunt

The shunt used with this method is a hollow cylinder of manganin, built into one of the water-cooled electrode holders. The first shunt built for this purpose was silver soldered into the copper electrode holder but this method was found to have softened the copper to an objectionable degree, so that later a double male-threaded construction was adopted. Potential connections to the shunt are of the knife-edge type usually employed for the precise determination of low resistances in the Kelvin double bridge. Figure 2 shows a photograph of the arrangement of connections and location of the secondary shunt in the electrode holder. The resistivity of the manganin was determined with the material in the form of a hollow cylinder, about six inches long, in a Kelvin double bridge. The cylinder had an external diameter of one and one-quarter inches and an internal diameter of one-half inch. Calculation shows that the skin effect of this bar is negligible. A twisted pair of conductors carry the potential connections away from the shunt in a direction perpendicular to the electrodes and parallel to the plane of the secondary loop. Care must be taken to avoid the introduction of vertical loops in the circuit, by properly backtracking and arranging the leads at the point where the conductors leave the shunt. The effectiveness of these precautions to eliminate induced voltages from the potential circuit should be checked experimentally. This may be accomplished by taking an oscillogram during the passage of welding current, with the oscillograph connected to the potential circuit which is short-circuited and insulated from the shunt.

The simplicity, directness, and precision of the calibration involved in the use of a secondary shunt make this method a

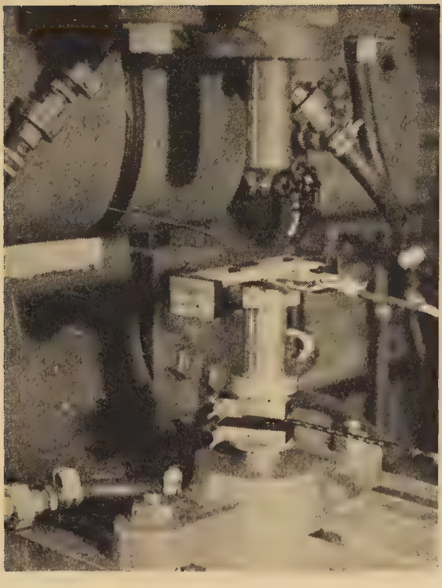

Figure 2. Arrangement of connections and location of secondary shunt in electrode holder

standard of comparison for other methods. If current were the only measurement desired, a simpler method than the use of the secondary shunt could be used. Our greatest use of the method has been in the determination of resistance and energy values in spot-welding circuits. This involves simultaneous determination of voltage drops in the parts of the circuit being investigated, and current measurement with the shunt. An example of this type of measurement is shown in the oscillograms of figure 3. The fact that these voltages and current are in phase indicates that inductive pickup has been eliminated, and that the quantities measured are purely resistive in character.

Electromagnetic Oscillograph—Primary Shunt

This method is simpler than the one previously discussed. A shunt for use in the primary circuit is a standard piece of apparatus, which is therefore easy to purchase. It may even be constructed without much difficulty and is simple to calibrate and install. The use of a primary shunt does not involve as much precaution as does the secondary shunt, to avoid the pickup of induced voltages.

In common with all methods involving measurement of primary current, it is necessary to make measurements of transformer ratio for all winding arrangements which are used. The transformer ratios are obtained by dividing the primary voltage by open-circuit secondary voltages. It is also necessary to correct the total primary current for its magnetizing component before calculating the secondary current. It is common practice to measure the magnetizing current under open-circuit conditions, and in the case of a welding machine, to subtract this from the total primary current arithmetically rather than vectorially. This procedure is not much in error since the power factor of the welding machine is usually so low that the magnetizing and load components of the primary current are nearly in phase. In many cases the magnetizing currents will be so small that they can be neglected, but this should never be done unless tests have shown this to be true. If transformers are overexcited or improperly designed, the magnetizing currents may be large.

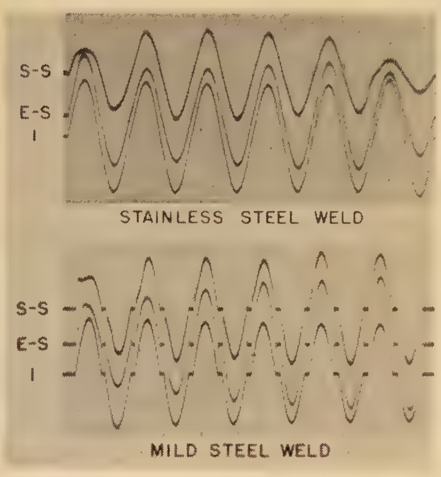

Figure 3. Oscillograms of voltage drops in secondary of spot-welding circuit

S-S—Sheet-to-sheet voltage drop
E-S—Electrode-to-sheet voltage drop
I—Voltage drop across shunt

Current-Crest Meter

This method of measurement uses an electromagnetic-oscillograph element to measure the drop in potential across a shunt in the welding circuit, usually on the primary side of the welding transformer. The oscillograph element deflects a light beam upon a translucent scale, usually graduated in millimeter divisions. No attempt is made to sweep the light beam across the screen and introduce a time axis. The reading of the meter consists in observing the amplitude of the deflection of the spot of light during the passage of the welding current. This reads the peak value of the current. If the wave form of the latter is sinusoidal, the effective value of the current may be calculated by well-known relations. With a little practice an observer may easily read these deflections to a half millimeter, and thus determine the welding current with an error of not over two per cent. These readings are most easily taken when synchronous closure of the circuit avoids the introduction of transients. If transients do occur, their magnitude may be observed. Readings may be taken by this method even if the time of current flow is only one or two cycles. The pointer has such low inertia that there is no problem with rapid response such as provides difficulty with an ordinary ammeter or even with the pointer-stop ammeter.

The writers are not acquainted with a meter which is actually manufactured and sold for this purpose. One of the elements of an ordinary portable, two-element oscillograph has been used by us for this type of measurement. Such a meter would appear to be a very useful laboratory instrument.

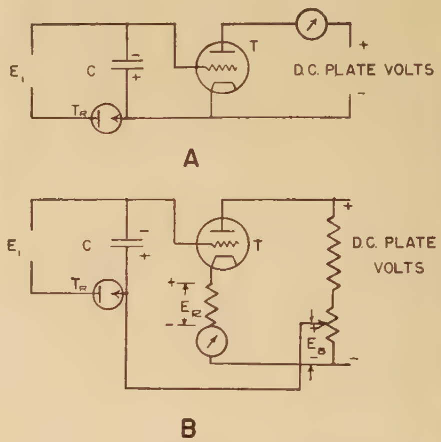

Figure 4. Fundamental vacuum-tube voltmeter circuit

Cathode-Ray Oscillograph—Primary Shunt

A limited amount of experience indicates that a cathode-ray oscillograph may be satisfactorily used in the same way as the current-crest meter above described. The calibration of this meter will not remain permanent so that a means for adjusting the amplifier gain to bring the meter into calibration must be available. A simple circuit, using a voltmeter, variable alternating voltage, and voltage divider, may be set up permanently to accomplish the above calibration easily and as frequently as desired.

A cathode-ray oscillograph is frequently available in a welding laboratory for checking wave forms, transient conditions, and phase-control settings, so that the possibility of using this instrument for current measurement may prove desirable.

A word of caution regarding the use of the cathode-ray oscillograph for current measurement is necessary because of the fact that these instruments are frequently affected by the magnetic field of the welding currents. This difficulty may usually be overcome by placing the instrument at a reasonable distance from the welding machine and by turning the instrument in such a direction as to minimize disturbance. The instrument must be calibrated in the exact position used for current measurement.

Pointer-Stop Ammeter

This instrument is commercially available together with calibrated leads and a clamp-on current transformer for use on the primary circuit. The ammeter consists of an ordinary instrument to which is added an adjustable stop which may be moved up behind the pointer. In measuring the short-duration spot-welding current, the pointer is gradually

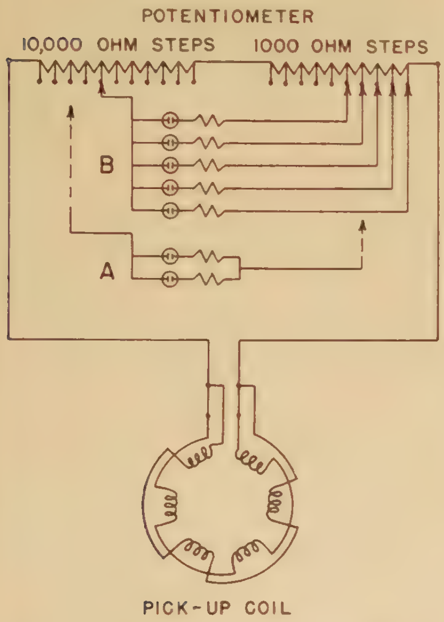

Figure 5. Fundamental neon-tube meter circuit

moved up the scale by adjusting the stop until the pointer just leaves the stop when a weld is made. Thus the current does not have to move the pointer all the way up the scale, but only a sufficient distance to indicate that the current is very slightly greater than the value set by the stop. To determine a value of current, it is necessary to make several welds in order to approach the correct setting of the stop for that value of welding current.

This instrument possesses a great advantage in simplicity of reading and ease of attachment to the circuit. It is very suitable for setting a welding machine to a particular value of current. It is necessary only to set the pointer, by means of the adjustable stop, to the value desired and then to adjust the current control until the making of a weld causes the pointer to slightly leave the stop. A further advantage of this method is that it may be used to determine the effective value of phase-controlled currents, which of course are not sinusoidal.

Among the disadvantages of this type of meter are the errors resulting with nonsynchronous circuit closure due to the transients produced, and the optimistic readings resulting from the double-frequency deflecting torque. The deflecting torque periodically varies above and below the control torque. When the pointer is moved up to the value of current which should be indicated, the tendency of the control torque to reduce the deflection below the average value is prevented by the pointer stop. Under these conditions the pulses of the deflecting torque above the average value tend to cause the pointer to jump away from the stop. A false indication of a higher value of current is thus given. In consequence of this we have commonly found a pointer-stop ammeter to consistently read five to eight per cent high. Less significant disadvantages consist of those com-

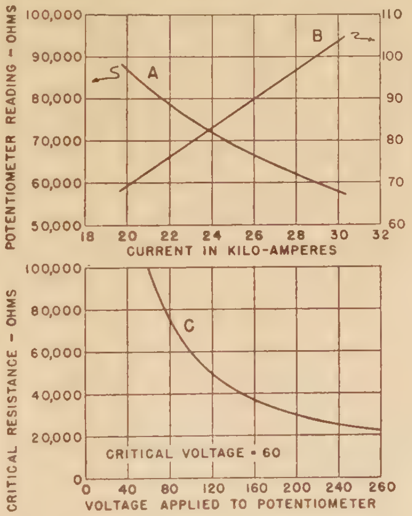

Figure 6. Characteristics of neon-tube meter circuit

A—Meter calibration
B—Toroid characteristic
C—Potentiometer characteristic

mon to all methods of measuring primary current, and which have already been discussed under the section describing the use of the electromagnetic oscillograph with a primary shunt. We have found also that the pointer-stop ammeter reading falls off when the time of current flow is three cycles or less. The amount of this falling off is not serious for a welding time of three cycles and amounts to only four per cent in two cycles.

1. For all numbered references, see list at end of paper.

Vacuum-Tube Voltmeter

Our experience with this type of instrument for the measurement of current has been made possible by the generosity of two men[1,2] who have been responsible for original development work. Each has kindly loaned us his instrument for study. Figure 4 shows the fundamental circuits in which the vacuum-tube voltmeter is used to measure the welding current in terms of the drop in potential across a shunt connected in series with the secondary circuit of a current transformer. The current transformer which we have used is designed for use in the secondary circuit by slipping the transformer over the electrode holder. The basic principle involved in this method is illustrated in figure 4*A*. The voltage drop, E_1, across the shunt on the current transformer charges the capacitor C through a rectifying tube T_R. This causes the grid of the measuring tube to become more negative, thus reducing the plate current. The capacitor is expected to retain its charge and thus maintain the reduced plate current for a sufficient time to permit reading. Figure 4*B* illustrates a second stage in the development of the circuit of this meter. Two desirable features of adjustability are provided in this circuit. The sliding contact with the indicated voltage drop, E_B, permits adjustment of the plate current to the de-

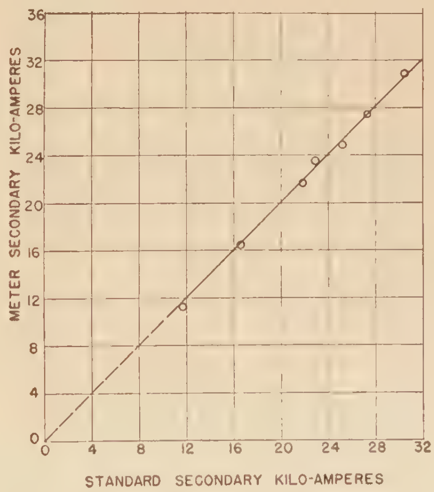

Figure 7. Comparison of primary-shunt measurements with simultaneous secondary-shunt measurements as a standard using an electromagnetic oscillograph in both cases

sired top-scale value, before each reading. The resistance associated with the voltage drop E_R in the cathode lead permits adjustment of the over-all sensitivity of the circuit.

One of the principal advantages of this instrument is that the readings are definite and may be obtained with one weld. Also, the secondary current may be measured directly. With circuit refinement to delay the charging of the capacitor the meter may be used to measure welding currents with large transients existing during the first few cycles. Such transients are caused by nonsynchronous closure of the welding circuit, and render inaccurate the measurement of current by almost all methods except the oscillographic.

The difficulties with the vacuum-tube voltmeter are associated with the current transformer and with the fact that it is a peak-reading instrument. The design of an iron-core current transformer to handle such heavy currents involves some sacrifice in portability. The introduction of so much iron into the secondary current loop affects somewhat the output of the welding machine. In our case with a short-throat machine, the output is reduced about three per cent when the current transformer is placed in position. This effect should be less noticeable with a machine of larger throat area.

The fact that the vacuum-tube voltmeter is a peak-reading instrument means that it is not suitable for nonsinusoidal currents such as are caused by the phase control of mercury-vapor tubes. A suggested method of dealing with these currents is impractical to use since it involves the use of full heat, which probably cannot be absorbed by the work.

Neon-Tube Meter

A meter that employs neon-glow lamps as voltage indicators in conjunction with a potentiometer and pickup coil was also investigated. The circuit of this meter is shown in figure 5. An air-core pick-up coil of the toroidal form is used in the secondary circuit of the welding transformer. The voltage induced in this coil is applied across a potentiometer. The original and basic voltage indicating circuit[3] employs two neon-glow lamps connected in parallel across the same points on the potentiometer as shown at figure 5*A*. Lamps having nearly the same critical voltages are selected for this purpose. As welds are made, the potentiometer connections are progressively changed until a point is reached at which just one of the lamps glows. The magnitude of the secondary current is then obtained directly by reference to the meter calibration.

In the present investigation it was desired to determine the approximate potentiometer setting more quickly and with fewer welds. Therefore a bank of five matched neon-glow lamps is employed as shown at figure 5*B*. By means of switches the entire range of the potentiometer can be explored in four steps. At each step the number of lamps that glow when a weld is made is observed and the approximate setting is that above which all lamps glow. Frequently, however, only one or two welds are necessary to obtain an approximate setting. A high resistance is connected in series with each lamp to avoid the shunting effect of those lamps that pass current. After the approximate setting is determined in this way the final meter reading is determined by means of the basic two-lamp circuit which has already been discussed.

A typical calibration of this meter is shown in figure 6*A*. This calibration was obtained by using the electromagnetic oscillograph and secondary shunt as the standard means of current measurement. The voltage induced in the toroid is a direct measure of the secondary current, if it is sinusoidal. A voltage-current characteristic of the toroid used in this investigation is shown in figure 6*B*. In order to control the voltage applied to the potentiometer, provision is made for connecting the pickup coils in series for measuring low currents and in parallel for high currents. This is very important because, as shown in figure 6*C*, the change in critical resistance for a given change in applied voltage becomes much greater as the applied voltage approaches the critical voltage of the lamps.

This type of meter is probably most useful in its basic form. Its primary advantage is its simplicity and low cost. When used simply as an indicator it does not necessarily have to be calibrated. For example, after the optimum welding conditions have been established for a given job, the reading of the meter can be recorded and then used in checking when the job is set up again at a later date. In our experience this meter was only used in measuring synchronously-timed currents. Its use with nonsynchronous timing should not be attempted since the

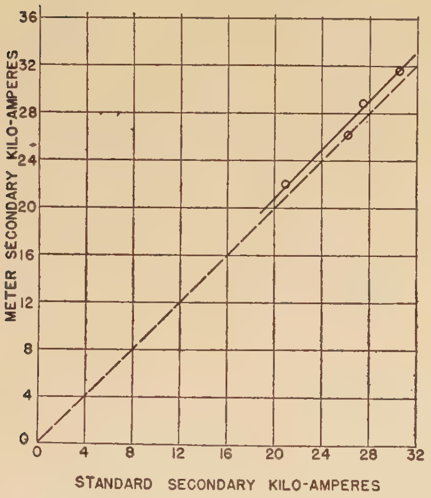

Figure 8. Comparison of current-crest-meter measurements with simultaneous secondary-shunt measurements as a standard

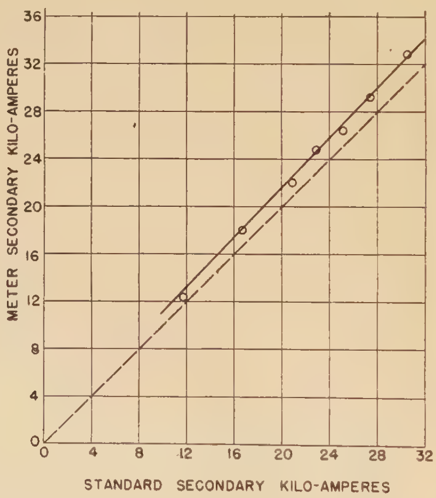

Figure 9. Comparison of pointer-stop-ammeter measurements with simultaneous secondary-shunt measurements as a standard

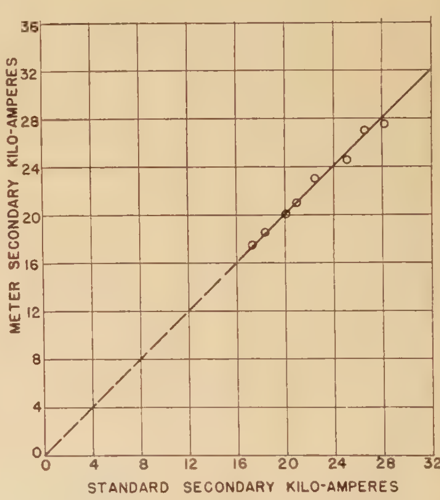

Figure 10. Comparison of vacuum-tube voltmeter measurements with simultaneous secondary-shunt measurements as a standard

maximum rate of change of welding current, which the meter actually measures, is only simply related to effective value for sinusoidal currents. Calibration and use of the meter requires that the critical voltage of the lamps remain constant with time, a relationship about which more information is needed. In general, experience thus far indicates that further development of this type of meter might prove to be worth while.

Comparison

Figures 7, 8, 9, and 10 are plotted for comparison of results by different methods. These are plotted using simultaneous secondary shunt measurements with an electromagnetic oscillograph, as a standard of comparison. The dotted curves would represent exact agreement. The solid lines represent the instrument readings. The primary shunt and vacuum-tube voltmeters give excellent agreement. The current-crest meter seems to have an optimistic tendency although the readings are within the limits of experimental error to be expected with this method—that is, about five per cent. The decidedly optimistic tendency of the pointer-stop ammeter is evident in figure 9.

It is hoped that this experience may prove helpful to those who have the problem of measuring such currents, and that it may be an encouragement to others to continue the development of these and possibly better methods of spot-welding-current measurement.

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2. **L. H. Frost**, Thomson-Gibb Electric Welding Company, Detroit, Mich.

3. A New General-Purpose Meter for Resistance Welding, **C. Stansbury**. The American Welding Society *Journal*, September 1935, pages 32–5.

Discussion

C. Stansbury (Cutler-Hammer, Inc., Milwaukee, Wis.): For several years we have been using the neon-tube type of meter. In our design the two neon tubes, calibrated rheostat, and switch for selecting the range are mounted directly on one side of the case in which the air-core toroid is built. Recent models are arranged so that the toroid can be opened up by means of a hinged construction for convenience in placing it around the welding electrodes or primary conductors. Also in recent models only one neon tube is employed. It has been found that these small neon tubes have a slightly different starting voltage for the two halves of the a-c wave and about the same result in bracketing the reading can be obtained with one tube as with two, with less chance for confusion.

With regard to using this meter on nonsynchronous circuits, although no great precision is obtainable, results sufficiently accurate for most practical purposes can be obtained by making a number of welds and using the highest setting which causes a glow on all of the welds. Welds on which the circuit happens to be closed so as to cause minimum transients correspond to the lowest setting of the instrument for which a glow is obtained. We use the meter in either the primary or secondary circuit as most convenient.

As we are not manufacturing this meter commercially, we have not been able to follow up certain things about which we would like to have more information as a matter of general interest.

Some time ago I had occasion to use the meter in the secondary circuit of a spot welder in which the primary current was controlled by ignitron tubes. These ignitron tubes were not synchronously controlled, but were controlled by a relay timer which caused random completion of the circuit. Under these conditions, the meter could not be used at all in the secondary circuit since the tubes glowed at all positions of the dial. When the meter was connected in the primary circuit, it worked satisfactorily. In using the meter in the primary circuit we ordinarily use a flexible, heavy connector and make several passes through the toroid.

Although I did not have an opportunity to determine the reason for this with an electromagnetic oscillograph as I wished, I did try to do so with a cathode-ray oscillograph. This instrument was so seriously affected by the magnetic field around the welder that I could not get any satisfactory results. As the authors state, the cathode-ray oscillograph is very unsatisfactory around a resistance welder for this reason.

A point which I would like to see brought out clearly, either in an appendix to this paper or elsewhere, is the difference in characteristics between an air-core toroid operating with negligible back ampere-turns and the conventional iron-core current transformer.

G. F. Gardner (nonmember; General Electric Company, Schenectady, N. Y.): By drawing attention to the necessity for accurate current measurements in welding, the authors have performed a great service to all who are in any way interested in spot welding. The measurements have evidently been carried out with great care and each method has been given the consideration which it deserves.

In connection with the electromagnetic oscillograph-secondary shunt method, the authors do not state the highest values of current which have been measured in their tests, but it may be of interest to note that measurements have been made on welding machines using similar shunts at currents up to 80,000 secondary amperes.

The electromagnetic oscillograph-primary shunt method is also of definite value. It would seem, however, that if it were to be generally applied, the use of a current transformer might be somewhat preferable to the shunt from the standpoint of ease of application and safety to the operator. Care should, of course, be taken to select a transformer whose limitations are not exceeded.

Current-Crest Meter. In considering this and the methods which follow, attention should probably be directed to the quantity which it is desired to measure—either the root-mean-square or the peak value of the current. Granted that it is possible to measure some transients and take account of their influence using this type of instrument, it nevertheless must be borne in mind that its indications are as dependent as any other of the crest measuring instruments upon the peak value of the wave. It was noted with considerable interest that the authors mentioned that such an instrument would be a useful laboratory tool. Experimental samples of such devices have been constructed and it is hoped that one will appear on the market shortly.

Cathode-Ray Oscillograph—Primary Shunt. The word of caution regarding the use of this instrument is certainly not out of place. Some of our experience indicates that a reasonable distance for an unshielded instrument may be as much as 40 feet from the welding machine.

Pointer-Stop Ammeter. It was gratifying to note the authors' experiences with this relatively simple type of instrument since at this stage of the welding measurements art, it appears that the choice is often between a simple means of current measurement or none at all. As regard the "optimistic" indications, this is not an essential feature of the pointer-stop ammeter and instruments can be so designed that they show but very little, if any, increase in reading due to the conditions mentioned by the authors.

The closing paragraph of the authors' work is especially significant and, in line with this, it may be of interest to mention further work which has been done along this line. A device has been made available known as the weld recorder which will give an accurate indication and record of the ampere-squared-seconds existing for a given weld. If the ampere-squared-seconds are not within preset limits, such as plus or minus five per cent, a bell rings and the machine is automatically locked out. The record will show whether the I^2t is above or below the limits. Nearly 100 of these have been made and have been found to have been very useful in establishing levels for resistance-welding measurements and, although their use has been restricted to comparative work at the present time, there is no reason why they could not be applied where definite values of ampere-squared-seconds are required. Space does not permit a full description of the instrument characteristics here, but it is hoped that it will be possible to publish an article containing this at an early date.

A. J. Corson and **E. W. Clark** (nonmember; both of General Electric Company, Lynn, Mass.): This paper is a very thorough and balanced evaluation of several existing methods of measuring spot-welding currents. It is hoped that it will stimulate interest, not only in the improvement of these methods, but in the application of them as well. The following discussion is based on a somewhat similar series of experiments, dur-

ing which a comparison of the secondary shunt and oscillograph was made with the pointer-stop ammeter and the vacuum-tube voltmeter.

Figure 7 shows excellent agreement between the primary- and secondary-shunt readings. The primary-shunt readings were presumably multiplied by the welding-transformer ratio as determined by the voltage method. This indicates an absence of errors due to such causes as saturation of the welding transformer, and varying current distribution in the secondary shunt, for the particular conditions of this test. It is doubtful if these conditions would apply to all welding transformers and all secondary loops. For these reasons, we prefer the use of the current method in determining this transformer ratio using a specially designed current transformer in the welder-transformer secondary since it more nearly simulates operating conditions and also avoids the necessity of measuring very low alternating voltages. Also in the interest of minimizing current distribution errors in the secondary shunt, this device was reduced to a minimum axial length 0.080 inch, as compared to the six-inch dimension described in the paper.

The response characteristic of the pointer-stop ammeter is, as indicated by the authors, somewhat dependent on the duration of the impulse. It would be of interest to know, therefore, what duration was used in determining the curve given in figure 9, also what interval of travel was allowed for the pointer oscillation. It would appear that this characteristic, while definite for an instrument of given design constants, is not universal, and by modification of these constants, improvement could be obtained in accuracy. In the meantime the application of a simple correction curve will result in a highly satisfactory degree of accuracy for all ordinary work.

W. F. Hess, R. A. Wyant, and **A. Muller:** In answer to the implied question in the second paragraph of Mr. Gardner's discussion, the maximum secondary root-mean-square amperes which we have had occasion to measure with the oscillograph and secondary shunt is 40,000 amperes.

Mr. Gardner makes a good point in his third paragraph with regard to the safety of the operator when using a shunt in the primary circuit. Care should be taken to mount the shunt so that there will be no occasion to come in contact with it while the primary circuit is energized, and to bring out insulated potential connections. The substitution of a current transformer for the primary shunt in oscillographic work is open to some objections. The wave forms may be distorted by transient currents produced in the secondary of the current transformer. These may be reduced by careful adjustment of the phase angle of this circuit to coincide with the angle of firing of the main power tubes. This adjustment would be an objectionable added complication. The calibrations involved are more complicated. The selection of a shunt to be used with the current transformer and oscillograph must be carefully made to secure good sensitivity and at the same time to avoid overloading the current transformer. Great care must be taken to insure continuity of the secondary circuit of the current transformer to avoid the hazardous voltages which are produced by an open-circuited current transformer. The more precise current transformers are usually not of the clamp-on type. It is therefore almost as difficult to attach them to the welding circuit as to install a shunt. Phase-angle errors are objectionable when simultaneous measurements of voltage drops and current are desired.

Our experience coincides with that of Mr. Stansbury in that the two electrodes of a single neon tube are as effective as two separate tubes in determining the final setting of the voltage divider which measures the toroid voltage.

In response to the suggestion in the last paragraph of Mr. Stansbury's discussion we offer the following. When a toroidal coil is placed around a conductor carrying an alternating current, a portion of the magnetic field set up by the current will link with the coil and induce a voltage proportional at any instant to the rate of change of the current. The peak voltage which we measure is therefore a measure of the maximum rate of change of current. Only for sinusoidal currents is the effective or heating value proportional to the maximum rate of change of the instantaneous value. Hence only such currents will be correctly measured by the peak value of the voltage developed in a toroidal coil.

A precaution that must be exercised in the use of a toroid is that the voltage must be measured without drawing appreciable current from the winding, since any current taken will tend to distort the flux set up by the current being measured, displacing it from within the toroid and causing the toroid voltage to drop.

In the case of the iron-core current transformer, a current must be permitted to flow in the secondary winding which balances at every instant the magnetic effect of the primary current. If such a secondary current does not flow, the flux density in the core will tend to rise and the secondary current will no longer be proportional to the primary current. Also the primary winding and iron core will act as a choke coil or reactance in the power line, and will absorb large energy losses from the line which it is incapable of dissipating. On the other hand if the resistance of the secondary circuit is kept sufficiently low, so that the current-transformer core does not saturate, then the current in the secondary will be a direct measure of the primary current even with considerable departure from sinusoidal wave shape.

In reply to the discussion of Messrs. Corson and Clark, the transformer ratios used in calculating secondary current from primary readings were, as stated in the body of our paper, determined by voltage readings. It is true that for the comparison tests presented in the paper the magnetizing currents were so low as to be negligible, indicating the absence of any approach to saturation of the welding transformer. Before using any method involving primary-current readings we have recommended the measurement of magnetizing currents for all settings of the welding transformer. If the magnetizing currents are found to be appreciable, as they may be on the higher taps of the transformer, the primary readings should be corrected for magnetizing current, before applying the transformer ratio to calculate the secondary current.

If the transformer core is approaching saturation, as evidenced by relatively high magnetizing current, there will be an error in determining the transformer ratio by voltage readings, due to primary leakage impedance. The voltage drop due to this impedance should be subtracted from the applied primary voltage to obtain the primary voltage induced by the mutual flux, which latter should be divided by the secondary open-circuit voltage to obtain the true transformer ratio. Owing to the difficulty of measuring the separate primary leakage impedance, another approach to the determination of transformer ratio is preferable. For those welding-machine connections which give rise to appreciable magnetizing current at rated voltage, the primary and secondary voltage readings should be taken with the primary voltage at such a reduced value as will avoid an excessive magnetizing current. The turn ratio may then be calculated from these readings without appreciable error.

The use of primary and secondary current transformers to determine the transformer ratio involves the use of special costly equipment not readily available, and would appear to involve at least as much chance for error in the two transformers and accompanying meters as should be expected with the voltage method. We have found no difficulty in measuring the low alternating voltages, with a good laboratory instrument. The axial length of the shunt used for secondary current measurement was approximately three-quarters inch between potential connections. The total length of manganin in the secondary circuit was about one inch. The six-inch dimension mentioned in our paper was the length of the manganin cylinder used in the calibration measurement to determine resistivity.

The duration of current flow for the curve given in figure 9 was six cycles. It had been determined that no definite reduction in reading occurred until impulses of less than four cycles duration were used. The interval of travel allowed for the pointer oscillation was approximately $^1/_{100}$ inch, which was about the minimum definitely perceptible.

Vector-Response Indicator

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THE performance characteristics of a communication circuit are often conveniently described in the form of a response curve which indicates the steady-state transmission of the circuit at frequencies within the range of interest. These curves can be obtained by making a sufficient number of individual measurements of transmission at various frequencies within the band of interest and plotting the results; however, considerable time may be saved by the use of a device which indicates directly the desired curve. Many such response-curve tracers are found in radio laboratories, with the curve of transmission or amplification as a function of frequency being obtained as a trace on a cathode-ray tube. However, strictly speaking, the transmission of a circuit, being the ratio of output voltage to input voltage of the same frequency, is a vector quantity having an angle as well as a magnitude—the angle being the phase angle between the output voltage and the input voltage. The response-curve tracers now in general use indicate only the magnitude of the amplification as a function of frequency. The vector-response indicator described in this paper is a unique apparatus that indicates directly both the magnitude and phase angle of the transmission as a function of frequency. This vector response of the circuit is indicated by a special type of pattern on the screen of a simple cathode-ray tube.

Figure 1. Comparison between elliptical-trace and reference-point methods of phase-angle measurement

Figure 2. Reference-point method used for a direct-reading high-frequency phase-meter

Some of the new communication systems recently developed have brought about an appreciation of the importance of phase characteristics. For accurate reproduction of a complex voltage wave the circuit must have, over the range of frequencies present in the wave, the properties that the magnitude of the transmission is constant and the phase angle is a linear function of frequency with the intercept at zero or $n\pi$. Except with circuits of long time delay, such as long telephone lines, little or no thought need be given to the phase characteristic requirement in sound circuits, since the ear is not sensitive to moderate phase displacements. However, in television and facsimile systems the complex wave shape must be preserved for acceptable reproduction, and this means that the desirable characteristics must be preserved in both magnitude and phase.

Phase-angle measurements above audio frequencies can be made from the elliptical trace produced on a cathode-ray tube screen when the two sine-wave voltages to be compared are impressed on the horizontal and vertical deflecting plates respectively. The phase angle can be calculated from measurements of the geometry of such a trace. If the phase angle were to vary periodically, as might be caused by a periodic variation of frequency, a series of elliptical traces would be produced, but this trace on the cathode-ray-tube screen would not indicate in a direct manner the variation of phase angle as a function of frequency.

For the vector-response indicator, it was necessary to develop a new method for measuring phase angles, which would give a more direct indication of the angle. This new method differs from the elliptical trace method in that one of the two voltages to be compared is applied to the vertical deflecting plates, the other voltage being used to give a reference pulse which is applied to the control grid of the cathode-ray tube. The reference pulse is obtained from some particular point in the cycle, such as the positive peak; this reference pulse is applied to the grid with such polarity that it causes the beam to become brighter. With a linear saw-tooth sweep applied to the horizontal deflecting plates, the sine-wave trace of the voltage on the vertical plates is seen, together with a bright spot at the instant that the other voltage reaches its positive peak (or other reference point). Thus, the location of the spot along the trace is a direct indication of the phase angle between the two voltages. Figure 1 shows a comparison between the ordinary elliptical trace and the reference-point methods for several phase angles.

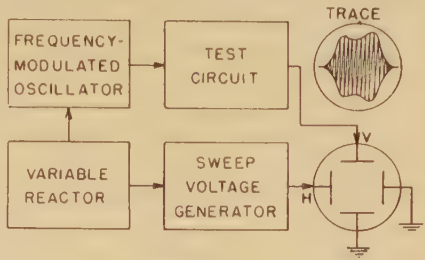

Figure 3. Simplified block diagram of a response-curve indicator

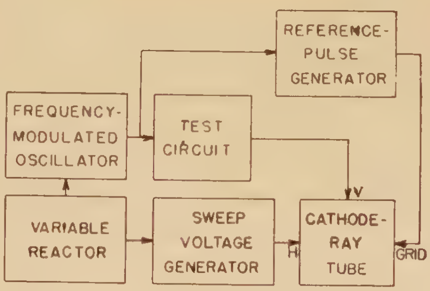

Figure 4. Simplified block diagram of a vector-response indicator

If no sweep voltage is applied to the horizontal deflecting plates, the trace will be merely a vertical line with a bright spot on it; the location of the bright spot indicates the phase angle between the voltages. An appropriate scale might be placed alongside this line and the phase angle read off directly. This is one way of using the reference point method to make a direct-reading high-frequency phase meter. However, to make the exact location of the spot along the line more evident, the pulse voltage

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Figure 5. Vector-response patterns

A—Simple resonant circuit

B—Double-tuned coupling circuit with greater than critical coupling

C—Three-element circuit with one inductance and two capacitances

D—Similar to preceding but with different ratio of capacitances

may be applied to the horizontal deflecting plates as well as the grid, giving traces such as figure 2.

Before considering the application of the reference-point method of phase-angle measurements to the construction of a vector-response indicator, it will be well first to review the operation of a simple response-curve indicator that shows only the magnitude of the transmission and not the phase angle.

If a constant sine-wave voltage is applied to the input of a circuit under test, the amplitude of the output voltage, with respect to the input voltage, indicates the transmission of the circuit at that frequency. If further, the frequency of the input voltage is slowly varied, but its amplitude always kept constant, then the variation of amplitude of the output voltage indicates, in some manner, the variation of transmission of the circuit with frequency (that is, the response curve). By varying the frequency periodically, and applying the output voltage to the vertical deflecting plates of a cathode-ray tube, a vertical trace, whose length varies periodically, will be produced. Then by applying a sweep voltage of the same period as the frequency variation to the horizontal deflecting plates, the variation of the length of the trace will be visible. The result will be a trace, symmetrical about a horizontal axis, whose envelope indicates the response curve of the circuit over the range of applied frequencies. Figure 3 shows a simplified block diagram for such a response-curve indicator.

The simple response indicator just described can be easily made into a vector-response indicator by a circuit addition. By adding a circuit which derives a pulse at some reference point in the cycle of the voltage applied to the input of the circuit, and then applying this pulse to the grid of the cathode-ray tube, an indication of the phase angle is obtained (figures 4 and 5). The trace produced now has a bright line appearing within the envelope of the trace. At any abscissa, the relation between the

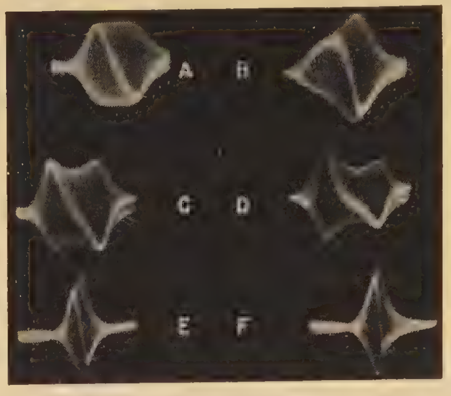

Figure 6. Vector-response patterns for a band-pass amplifier with a double-tuned input circuit and a single-tuned output

A—Proper adjustment of all circuits

B—Similar to *A* with single-tuned circuit tuned above mid-band frequency

C—Insufficient loading in double-tuned circuit

D—Similar to *C* with single-tuned circuit tuned below mid-band frequency

E—Less than critical coupling in double-tuned circuit

F—Similar to *E* with single-tuned circuit tuned above mid-band frequency

ordinate of this bright line and the ordinate of the envelope indicates the phase angle of the circuit at the frequency corresponding to the particular abscissa. If the reference pulse is obtained at the positive peak of the input cycle, then when the bright line coincides with the top envelope, the output voltage is in phase with the input. When it coincides with the lower envelope, they are 180 degrees out of phase. It may be desirable at times to have a 90-degree leading phase angle indicated by coincidence with one envelope and a 90-degree lag by coincidence with the other envelope. This can be accomplished by producing a 90-degree phase shift between the voltage applied to the test circuit and that applied to the reference pulse generator.

A simplified block diagram of the vector-response indicator is shown in figure 4. The variable reactor can be a motor-driven variable capacitor, or a reactance tube, that is, a vacuum-tube circuit arranged to appear like a reactance. The sweep oscillator is synchronized with the variable reactor so that they have the same period. A simple reference-pulse generator might be a vacuum-tube biased beyond cutoff to such an extent that plate current flows only at the positive peak of the applied alternating voltage.

Some illustrations of traces obtained on a vector-response indicator using simple circuits are shown in figure 5. It will be noted that in figure 5*C* there are two zero power factor frequencies, while in figure 5*D* the circuit has capacitive reactance at all frequencies. Figure 6 shows results using a band-pass amplifier with one double-tuned coupling circuit and one single-tuned circuit operating at 175 kc.

All the oscillograms were photographed directly from a small cathode-ray tube (type 902) having a screen of two inches diameter. The apparatus constructed for these tests differed from the simplified block diagram of figure 4 by the use of a beat-frequency signal generator instead of a simple oscillator to generate the desired signals. Properly designed

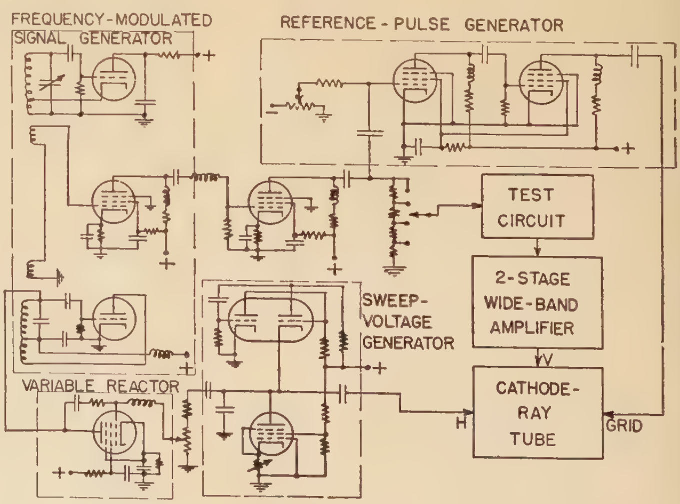

Figure 7. Circuit diagram of vector-response indicator used in tests

Causes of Corrosion of Fine Copper Wires Carrying a Potential

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COPPER CORROSION is a serious problem in electrical equipment which uses very fine wires carrying a potential, the outstanding examples being various types of coils used in radios and ignition systems. The usual type of corrosion involves the formation of green material on the surface of the wire, which is obviously due to chemical reaction of the copper with materials in contact with it. As this chemical reaction progresses at a given point in the wire, the cross section of unchanged copper gradually diminishes until finally a break occurs, opening the circuit and rendering the coil useless.

Previous Views of Copper Corrosion

In the past, the question of the actual cause or causes of copper corrosion has often been approached by means of inference rather than experiment, and it is, therefore, not surprising that widely varying views have been held by different people. Probably one of the most popular beliefs is that free acids in materials contacting the wires are responsible. This belief has been the basis of specifications of "acid-free" papers and tapes to be used in the construction of coils. In some cases, specifications are given which require that a distilled water extract prepared by some standardized technique must fall within certain limits of pH. More recently it has been recognized that acids are not the only substances which might cause this effect. Assuming that electrolysis is the fundamental cause of corrosion, it would follow that not only acids but also bases and salts would produce the same effect.

Another similar view is based on the idea that the rate of corrosion of copper wires in contact with a given material is proportional to the conductance, or inversely proportional to the insulation resistance of the material in question.

Again, it has been a common observation that copper corrosion is most serious in high humidities, and this fact has given rise to the belief in some quarters that moisture absorption is the primary factor in corrosion.

Corrosion by Adhesive Tapes

The present study was primarily concerned with the causes of corrosion by adhesive tapes used in the fabrication of coils, and although the results have implications of broader significance, we shall first deal briefly with the specific problem which prompted this work.

Adhesive tapes may be considered as a combination of two functional parts, the adhesive and the backing. We may conveniently consider these in order.

At the present time, electrical-tape adhesives are mainly of the rubber-resin type, although in the past, glue has been used. The use of the latter may be disposed of rather summarily, as it is now known that glue hydrolyzes rather rapidly in high humidities at elevated temperatures, with the production of organic acids of sufficient activity to be a major cause of corrosion. The ill-advised attempts to correct the difficulty by using dialyzed glues, which could be made substantially electrolyte-free, resulted in only a transitory improvement; because in use, the glue itself was a source of electrolytes.

Experimental Study of Corrosion

In view of the fact that corrosion by the more satisfactory electrical tapes developed so slowly under any practical operating conditions, it was necessary to develop an accelerated corrosion test. We therefore canvassed the radio industry, and finally standardized on a test similar to the most severe ones in use. The arrangement consists essentially of two parallel bare copper wires at a potential difference of 90 (later increased to 250) volts direct current held under tension against the surface to be tested, under conditions of 90 per cent relative humidity and 120 degrees Fahrenheit. The specimen was placed on the bowed surface of a moulded block with two binding posts at each end and was held in position by two parallel bare copper wires, spaced $^3/_{16}$ inch apart and each held under slight tension by a pair of binding posts. Originally, number 40 wires were used, but later it was found more satisfactory to use number 32 wires and estimate the amount of corrosion microscopically. At 90 volts, the usual duration of the test was four days.

Glues, however highly purified, were found in this test to be highly corrosive. Purification delayed slightly the beginning of corrosion, but did not result in an important improvement.

The rubber-resin type of adhesive, on the other hand, is not a cause of corrosion, provided that reasonable care and common sense is used in its formulation. The usual adhesive made from rubber, rosin, and zinc oxide also yields, during artificial aging which would correspond to at least five years of natural aging in the absence of light, products which contribute nothing toward corrosion. Thus, in spite of the fact that the very term, "acid", to the layman, is the symbol of death and destruction, we find that an adhesive which contains a large percentage of abietic acid is noncorrosive. Abietic acid and similar resin acids are so weak and so difficultly soluble in water that their acid properties may be neglected.

Corrosion by Cellulosic Backings

The elimination of the adhesive as a factor in copper corrosion by pressure-

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amplifiers were added where necessary. Figure 7 shows the circuit diagram of the apparatus.

Conclusion

An apparatus has been described that is believed to be new and useful. From the ideas presented there can be developed various phase measuring equipment, such as direct-reading high-frequency phase-meters, phase-characteristic indicators, phase-curve tracers, and time-lag-curve tracers, as well as the vector response indicator described. The increasing use of television and frequency modulation systems should make phase-measuring apparatus such as these of increasing importance in circuit investigation and testing.

Table I. Insulation Resistance at 120 Degrees and 90 Per Cent Relative Humidity

	Megohms	
	Unextracted	Extracted
Rayon (viscose)	3	112
Linen	4	
Silk	20	4,000
Wool	1,700	1,400
Cellulose acetate	5,000	10,000

sensitive tapes leaves the backing as the remaining possibility. At first it was assumed that impurities in the paper or cloth were responsible, and we therefore tested a wide variety of papers ranging from cheap wrapping papers through purified papers for electrical uses, and finally, the most highly purified alpha-cellulose obtainable, in the form of ash-free filter paper. The extracts of these various papers, prepared according to ASTM standard *D*-202-34*T*, section 45, showed large differences in both pH and electrolytic conductivity, but although the low-grade papers caused very bad corrosion, we were surprised to find that there was no significant difference in this respect between the most highly purified alpha-cellulose and any good saturating paper. The inference was plain that the cellulose itself (in the presence of water) was causing corrosion, but we were at first so reluctant to accept this conclusion that we attempted to purify the cellulose further by exhaustive extraction, in a syphon extractor, with highly purified water. An additional extraction with highly purified ether was performed in some cases. However, all such purified samples behaved similarly, and there was no noticeable improvement over the unextracted samples. A similar study of the effect of purification on cotton fabrics yielded exactly parallel results.

Now, if cellulose itself, in the presence of water is a source of copper corrosion, cellulosic materials other than paper or cotton ought to show the same behavior. We therefore studied samples of linens and viscose rayons, all free from loading or sizing materials, and we found that they caused corrosion at essentially the same rate as cotton or paper. Regenerated cellulose films such as are used as the base for Cellophane behaved in the same manner. Furthermore, we found that exhaustive extraction of any of these materials as in the case of paper, produced no perceptible improvement. Other fabrics made from natural fibers, such as silk and various kinds of wool, were also found to cause corrosion, but wool was very much superior to all other natural fibers in this respect. Again, it was obvious that impurities were not responsible because exhaustive extractions failed to produce any improvement. It is rather surprising that silk is not much better than cellulose in the matter of corrosion whereas wools, which are also protein fibers, are very much better than either silk or cellulose.

Noncorrosive Materials

The elimination of paper and all fabrics made from natural fibers then led us to search for a synthetic material which would be free from corrosive nature. Briefly, it has been found that there are a number of materials which are satisfactory from a chemical viewpoint; for example, cellulose esters and ethers, rubber and some of its derivatives, and a number of synthetic resins from the polymerization of styrene, vinyl derivatives, or methacrylates. Of the above materials, cellulose acetate is the most economical to use and the one with the best mechanical properties; consequently it is the only one which has been exhaustively tested over long periods of time. It has been tested both in the form of transparent sheets and in the form of cloth woven from the fibers, and apparently is completely free from tendency toward copper corrosion. There is every indication that a fine copper wire in contact with cellulose acetate will last as long as one suspended freely in air.

Possible Causes of Corrosion

After having been compelled to recognize the fact that cellulose itself was a source of corrosion, the next step was to inquire into the reason and several possibilities were investigated. One obvious possibility, to which reference has already been made, is that the corrosive nature of a given substance is a function of its absorptive (or adsorptive) capacity for water. Only a cursory examination of the facts, however, is sufficient to show that this is not so. Wool shows a much higher moisture absorption than cotton, yet is far superior with regard to freedom from corrosive nature. Also, cellulose acetate shows a moisture absorption which is reported to be over half as great as for cellulose itself, yet it is completely free from corrosive nature.

If corrosion is fundamentally due to electrolysis, a flow of current would necessarily be involved. Conductivity (or its reciprocal, insulation resistance), ought therefore to parallel the rate of corrosion by various test samples. Accordingly, a series of measurements was made on fabrics of approximately 0.006 inch thickness as nearly alike as possible in density of weave, and all free from loading and sizing materials. The specimens were mounted on binding posts $1^1/_2$ inches center to center, and were conditioned for 48 hours at 120 degrees Fahrenheit and 90 per cent relative humidity before measuring resistance under those conditions. A parallel series of measurements was then made on the same fabrics after they had been exhaustively extracted with highly purified water. We believe that the results are sufficiently striking to merit including them (table I).

A glance over the trend of the insulation-resistance values for the unextracted samples might seem to indicate that the real explanation of corrosion was to be found here. However, when we pass on to the values for the extracted samples, we find that the enormous increases in resistance for rayon and silk completely refute the idea that corrosion parallels insulation resistance. For example, a 20-fold, or more, increase in insulation resistance by extraction results in no appreciable decrease in corrosive nature. There still remained the possibility that insulation resistance might decrease rapidly during the period of the corrosion test, but this was shown not to be so. It seemed impossible that the corrosion process could be independent of any flow of current, but our results indicated clearly that flow of current in itself was not the controlling factor.

Electrochemical Oxidation as a Cause of Corrosion

As a last resort, we attempted to test the possibility that electrochemical oxidation of cellulose, in the presence of water, might take place at the anode, and we were finally rewarded with the correct explanation of the observed copper corrosion. If the cellulose were oxidized at the anode, water-soluble organic acids would be formed and ought to be capable of detection. For test purposes, it was necessary to replace the copper wires by some metal which would not react with such acids. We therefore used platinum wires in contact with rayon and carried out the test in other respects exactly as the standard corrosion test described above. At the end of six days, the specimen of rayon was examined for chemical changes in the cellulose. By means of Harrison's reagent[1] it was found that the cellulose had acquired reducing properties throughout the whole area between the wires, indicating either hydration or

oxidation. By means of indicators, it was shown that free acid was present only along a thin line which had been in contact with the positive wire. It is a commonplace fact that green copper corrosion always appears on the positive wire. Hence, the production of water-soluble acids at the anode offers an explanation of this corrosion which appears to be inescapable. Incidentally, it can readily be demonstrated on a large scale that cellulose is electrochemically oxidized to a complex mixture of water-soluble organic acids. By grinding up cellulose fibers and suspending them in water in an oxidation cell, large quantities of these acids may be obtained.

The above explanation of corrosion also offers an obvious explanation of the failure of exhaustive extraction to reduce appreciably the corrosive nature of paper or cellulose fabrics. If appreciable amounts of water-soluble acids are formed by the oxidation of cellulose, the presence or absence of traces of electrolytes in the original paper or cloth is quite unimportant. Therefore, as far as corrosion problems are concerned, extremely rigid specifications on paper or cloth probably do not accomplish anything useful. This does not imply, of course, that any low-grade material is just as good as a highly purified one, but merely that there is a definite limit to the usefulness of purification. The initial presence of large amounts of electrolytes is, of course, bound to have an effect.

Only in the case of cellulose has it been possible, by means of sensitive tests, to demonstrate under conditions to which radio coils are normally exposed, what actually takes place during the development of corrosion. The development of corrosive properties in protein materials may be largely or even altogether due to hydrolysis instead of oxidation. One might, therefore, tentatively specify as a noncorrosive material one which is nonelectrolytic itself and which is (*a*) resistant to oxidation and hydrolysis or (*b*) yields nonelectrolytic products.

Rubber is an example of the latter type, whereas the cellulose ethers and esters are quite resistant to oxidation. Apparently all that is necessary to increase enormously the resistance of the cellulose molecule to oxidation, is to replace the hydroxyl groups. It appears to be quite immaterial whether they are replaced by the acetate, nitrate, or any one of various other groups; the result is always a great increase in resistance to oxidation. Thus we find that any one of these cellulose derivatives is apparently satisfactory as far as corrosion is concerned, although cellulose acetate is the only practical possibility at the present time.

Mechanism of Copper Corrosion

During the corrosion of copper wires under a potential, the fundamental change that takes place is the oxidation of metallic copper to cupric ion ($Cu-2e=Cu^{++}$). If we designate the negative ion which appears in combination with Cu^{++} as A^-, the compound may be written as CuA_2. The latter accumulates as a green cupric compound on the positive wire. The two prerequisites for the appearance of green corrosion are, therefore, oxidizing conditions at the copper wire and availability of a negative ion. It is obvious that the deficiency of electrons at the positive wire provides the oxidizing conditions, and if an electrolyte is present in the path between positive and negative wires, all that remains is to provide mobility for its ions. At high humidities, water which is absorbed, or adsorbed, by cellulose provides the medium in which the ions may migrate. In low humidities, that is, in the virtual absence of free water, corrosion is, in general, exceedingly slow.

It is obvious that the presence of any electrolyte which will yield A^-, will contribute toward the formation of the green product of corrosion, CuA_2. It is immaterial whether the electrolyte is an acid, HA, or a salt such as NaA. Thus, pH measurements are without significance in predicting or explaining corrosion, as a neutral salt may be at least as harmful as an equivalent amount of acid. In fact, if we are considering a very weak acid such as abietic acid and its salt, the latter will be much more harmful. The acid itself may be so weak or so insoluble, or both, that it will be practically un-ionized, whereas the salt will be highly ionized. It is a familiar fact that rosin itself has no corrosive action, whereas sodium abietate (rosin size) is highly corrosive.

Now to return to the specific case of cellulose, electrochemical oxidation will take place at the wire at which oxidizing conditions exist; namely, the positive wire. The organic acids formed by oxidation will thus make immediately available their negative ions, and conditions for formation of a salt, CuA_2, are complete.

If, however, we examine this mechanism of corrosion critically, we find that in order for corrosion to proceed by deposition of negative ions of organic acids on the positive wire, a corresponding flow of current would necessarily take place. This would require that corrosion be a function of conductivity and would appear to be in direct conflict with our finding that samples of cellulosic fabric, extracted and unextracted, respectively, show no correlation between rate of corrosion and conductivity. This conflict, however, may be apparent rather than real, for the reason which follows.

Suppose we examine two samples of cellulose fabric, one contaminated with a trace of active electrolyte and one exhaustively purified. The initial insulation resistance of the former will be greatly decreased, particularly in high humidities, by the presence of electrolyte; but one might expect that with continued application of potential, the electrolyte would be used up and the insulation resistance would rise to approximately that of the previously purified sample. This is actually what we observe experimentally. In addition, the disappearance of the contaminating electrolyte would leave the cellulose itself as the only remaining source of corrosive material, and one would expect that the continuing rate of corrosion would approximate that of the previously purified sample. Thus we see that the amounts of corrosion caused, respectively, by purified cellulose with a high insulation resistance and by material contaminated by electrolyte, will differ only by the corrosion caused by the contaminant. This might well be so small as to be unimportant.

Impregnation as a Protection for Corrosive Materials

In view of the high cost of cellulose-acetate films and cloth, it would be highly desirable to use paper or cotton as a base material for tape backing and impregnate or coat with some noncorrosive material. A number of attempts have been made to develop a practical construction of this type, but the result has been consistent failure. It must be borne in mind that a satisfactory material for the purpose must be sufficiently tough so that contacting wires will never penetrate the film of impregnating or coating material and come in contact with the cellulose. Such noncorrosive materials as paraffin, shellac, and other highly thermoplastic or excessively brittle materials are obviously inapplicable. Cellulose acetate itself is satisfactory, but as a matter of experience, such a heavy coat is required to give complete protection of the surface, that no economic advantage could be gained. In addition, when such material was slit, cut, or torn, cellulose fibers were exposed,

thereby generating a region at which corrosion could take place.

To sum up, we feel that the most satisfactory and practical construction for a corrosion-free electrical tape is cellulose acetate coated with a good quality rubber-resin adhesive.

Reference

1. Society of Dyers and Colorists *Journal*, volume 28, 1912, page 359.

Discussion

B. W. Erikson (General Electric Company, Schenectady, N. Y.): H. N. Stephens and G. B. Gehrenbeck are to be congratulated on their masterly and timely solution of a very difficult problem. It is well-known to anyone who for years has been connected with the manufacturing problems incident to fine-wire coils that so-called corrosion failures have constituted the majority of all field failures.

The successful use in recent months of so-called noncorrosive material has plainly indicated that the writers have correctly analyzed the causes for fine-wire corrosion failures. Coils operated on an accelerated test at 100 per cent humidity in 40 degrees centigrade ambient over periods of months have conclusively proved that if the ordinary cellulose materials such as tapes and papers are excluded from the coil structure and acetate, mica, or asphaltic materials substituted the coils will last practically indefinitely. As a comparison, coils made with the best so-called acid-free cellulose materials on these accelerated tests seldom last beyond ten days, whereas the so-called corrosion-free coil construction shows a life expectancy of at least four months under these very severe tests. Our tests agree with the authors' that moisture is an essential factor in corrosion failures.

In relation to the paragraph on impregnation as a protection of corrosive materials it has been quite definitely shown that even three or four coats of a good baking varnish is not enough to protect against fine-wire corrosion. For this reason we agree with the authors that the only really satisfactory solution is the strict adherence to corrosion-free materials or in other words the exclusive use of cellulose acetate, mica, and asphaltic materials.

G. B. Gehrenbeck: Mr. Erikson lists three materials which he considers as corrosion free; namely, cellulose acetate, mica, and asphaltic materials. When tested across a flat unbroken surface, mica is indeed noncorrosive. However, when the test is made between two edges or along one edge, we have found rather low resistivity and some evidence of corrosion. Apparently, some electrolyte is present between the laminae of the mica, which under high humidity may carry an appreciable current. In a coil, there is always the possibility that the fine wires will come in contact with the edge as well as the face of the insulation. On this basis, mica appears to be less desirable for the insulation of fine wire coils than does cellulose acetate.

Contact Phenomena in Telephone Switching Circuits

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Synopsis: The phenomena occurring at the closing and opening of contacts carrying weak currents have been investigated by means which include a study of the high-frequency transient voltages and currents. These influence the erosion in a complex manner which varies with contact materials, surface conditions, and surrounding atmosphere. Three principal classes of effect have been distinguished. These are: (1) Disruptive spark-overs initiating a series of metallic arcs lasting less than a microsecond each. (2) A nitrogen-gas glow discharge at about 300 volts, preceded by a brief group of disruptive spark-overs. (3) High field breakdowns due to cold point discharges which cause transient metallic closures of approaching contacts and similar transient reclosures of separating contacts.

THE operation of a telephone system depends on the proper performance of many millions of electrical contacts, a large proportion of which are in relays. The relays must be designed for a life during which they operate from as few as 5,000 to as many as 400,000,000 times. Although the nominal currents and voltages carried by the contacts are rather low, the large number of operations may cause erosion which in a very small percentage of cases leads to failures to close or open the circuit. The difficulties caused by even very rare failures make the control of contact erosion a problem of major importance for the telephone companies.

Research and development work on contacts has of course been carried on continuously since very early in the development of the telephone system. The aim is to design contacts to have a life at least equal to that of the apparatus of which they form a part and to require a minimum of maintenance. Although this aim has in general been successfully met there have been some cases in which the contacts have worn out too rapidly.

Although it has long been realized that contact operation necessarily involved the generation of high-frequency transients, there was at first no apparatus available which would permit these transients to be studied. The Dufour oscillograph was for a long time the only instrument which covered the range of frequencies involved. It was employed as early as 1926 in studies of contact sparking but it was very cumbersome in use, often introduced artificial conditions into the circuit of the contacts, and progress with its use was necessarily very slow. During the past few years rapid advances have been made in the development of glass-envelope cathode-ray oscillograph tubes. By employing the latest types of tubes, and combining them when necessary with wide-band high-frequency amplifiers and with circuits which permit synchronization of the tube sweep circuit with the contact operation, it has been possible to make thousands of observations in the time originally taken by a single oscillogram, and to cover the entire range of currents, voltages, and frequencies involved. We now have available means which will permit the visual observation of transient voltages at frequencies as high as 400 megacycles per second, and transient currents with components reaching 20 megacycles per second. Single pulses lasting a small fraction of a microsecond, and complex transients containing components as high as 5 megacycles can be clearly resolved and photographed while the envelopes of still higher frequencies can be recorded.

In order to study the transients at contacts operating at 50 volts and steady currents under one ampere, in common types of telephone circuits, voltages as high as 2,000 and currents reaching 20 amperes must be within the range of the apparatus. A detailed description of the apparatus will not be attempted in this article, but the results of observations made with it and photographs of the more significant transient components will be presented.

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The author wishes to acknowledge the collaboration of E. T. Burton in the observation and explanation of the phenomena and the assistance of I. E. Cole in the development of the testing apparatus; of Mr. Glass, who developed the cathode-ray tubes; and that of many engineers and physicists in our organization, in particular Messrs. Mathes, Hogg, Goucher, and Pearson, in the formulation of some of the hypotheses expressed.

Study of the currents requires an amplifier as an impedance matching device and some circuit conditions make a shielded input transformer necessary. An input impedance of from 0.5 to 2 ohms, a voltage gain of about 75 times, and a substantially flat characteristic of output versus input from 20 kilocycles to 20 megacycles are usually employed. Lower frequencies may be observed with other amplifiers and the range from zero to 10,000 cycles per second is studied by means of the "rapid record" oscillograph.

With earlier cathode-ray tubes, beam currents of 40 microamperes at 5,000 volts were employed. The latest tubes give a beam current of about one milliampere at this voltage. A Leica camera with an $f/1.5$ Xenon lens and ultraspeed panchromatic film has been used in most of the photographic work. The photography is complicated by the presence in a single transient photograph of some components in which the beam speed may be a thousand times as fast as it is in others. However, beam speeds in excess of 200 kilometers a second are photographed, and a continuous sine wave of 5 megacycles frequency may be clearly resolved on a single transit. Sweep speeds which permit resolution of much higher frequencies are employed for visual observation, where the transient component being studied can be found by frequent repetition of the contact operation. As the occurrence of a particular component varies in time of its position in the entire transient, very high sweep speeds are impractical for photography as a prohibitively large proportion of exposures would be blanks. A sweep speed of about 15 kilometers per second is about as high as is useful except in some special cases.

We may commence the discussion by setting up what appears to be a very simple circuit (see figure 1), a pair of contacts, one of which is connected by a length of wire to a relay winding, which is in turn connected to one pole of a 50-volt battery. The mate contact and the other pole of the battery are grounded by very short wires. The oscillograph is arranged so that the voltage between the contacts and the current through them can be observed, great care being taken to insure that the added apparatus does not appreciably change the circuit characteristics even at very high frequencies. A low-power microscope may be set up to observe the operating area of the contacts.

When the contacts close, the first thing that happens is the discharge of the relay structure (a capacity) and of the wire through the contacts. The wire may be thought of as a radio antenna, more or less open-circuited at the load relay-winding terminal, and either grounded or opened at the contacts. The wire forms an oscillatory circuit of moderately heavy damping with a surge impedance of about 100 ohms. As it is charged to 50 volts, when the contacts come together an oscillation having a peak current of 0.5 ampere occurs, and is over before the steady current through the relay winding has more than started to build up. The frequency of the line oscillation depends on the length and other characteristics of the wire, but it is (in the telephone plant) rarely lower than 500,000 cycles, and on short leads it may be many megacycles. Fortunately most contacts are not much affected by closing a half ampere. Erosion and build-up will occur, but at rather slow rates, and they are usually completely obscured by effects due to the contact opening. Of course, if the contacts bounce,* the effect will be more complex, but we are assuming for the moment that they do not bounce. The structure of the relay itself, including the pair of springs separated at its base by an insulating sheet, is also an oscillating circuit. We have not been able to get inside of this circuit and measure the current surge but its oscillation frequency seems to be about 250 megacycles for certain telephone relays.

Now suppose that the simple circuit of our closing contacts is complicated by an additional wire connected to the contact-spring terminal. This is also charged to 50 volts before the contacts close, and being a second circuit of a hundred ohms surge impedance in parallel with the original wire, the current peak discharged through the contacts will now be about one ampere. But now the contacts are likely to act differently.

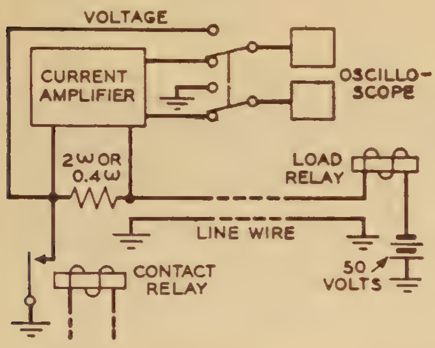


Figure 1 (left). Typical relay and contact circuit

Figure 2 (right). "A" transient starting with metallic arc (voltage)

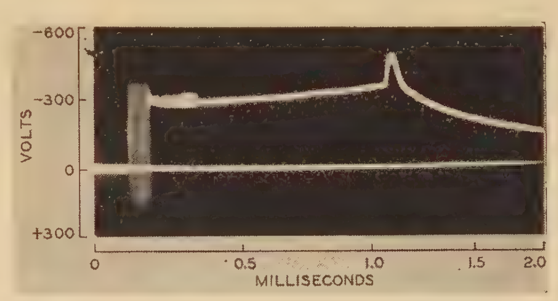
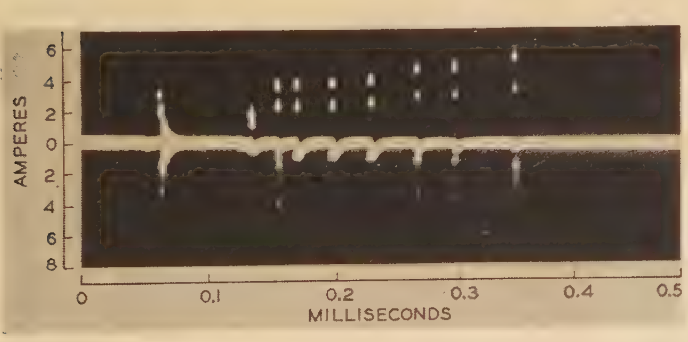
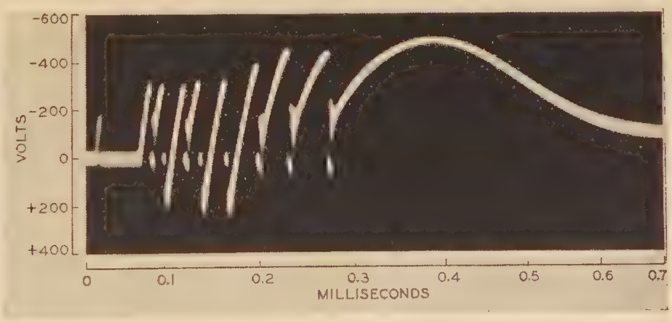


Figure 3. Entire "B" transient (voltage)

Figure 4 (below). Entire "B" transient (current)





* Bounce, as distinguished from chatter, reopens the contacts after several thousandths of a second.

About a microsecond after the current reaches its peak, but before the charge in the wires has been completely dissipated, the circuit is interrupted and the discharge stops. A spark, which is visible in the microscope, suggests that the current-carrying areas have been exploded and blown apart. A few microseconds later they again close and the rest of the energy is discharged, but some of the contact metal must have been destroyed.

If several "idle" wires are attached to the contact, the current surge, and the number and duration of the contact reopenings increase, but not usually in direct proportion to the number of wires. If the idle wires are attached to the load relay-winding terminal instead of to the contact, the current is smaller, as the length of single wire from relay winding to contact is effectively in series with them.

In the telephone relay circuits which we are considering, the steady-state current plays little part during contact closing if the contact-carrying relay is properly adjusted, as the contacts come to rest while the current is still held at a small fraction of its final value by the inductance of the load relay winding.

Under some conditions which are more likely to occur in telegraph than in telephone circuits the contact closure phenomena are somewhat different than those described above. Assume, for example, that the potential between the open contacts may be adjusted in a range between 30 and 250 volts while the final direct current is limited by circuit resistance to less than 0.5 ampere. At the low voltage, observations of the current and voltage transients indicate that the closing

Figure 5. Initial opening and reclosure—"B" transient (voltage)

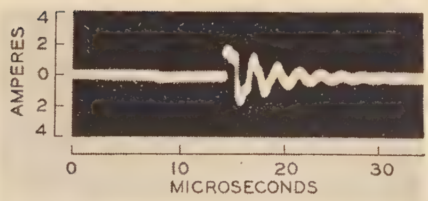


Figure 6. Initial opening and reclosure—"B" transient (current)

contacts merely discharge the line. As the voltage is raised so that the current surge peak is in the range between 0.5 ampere and 1 ampere the reopenings, due presumably to overheating of the contacting areas by the discharge, are observed. These become more frequent as the voltage and current increase, and a new type of current surge begins to appear. This is placed on the time axis ahead of the point at which the initial closures have been occurring (usually five to ten microseconds earlier) and consists of one or more irregularly spaced heavily damped pulses of current lasting only a small fraction of a microsecond and evidently discharging only a minute amount of the energy stored in the system. They occur perhaps once in a

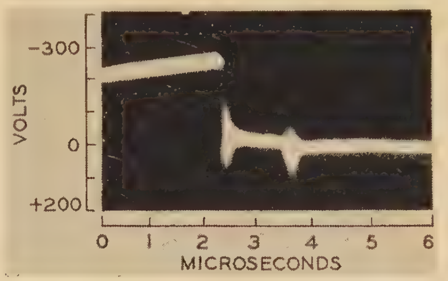


Figure 7. Initial opening and reclosure—"B" transient (voltage) rapid sweep

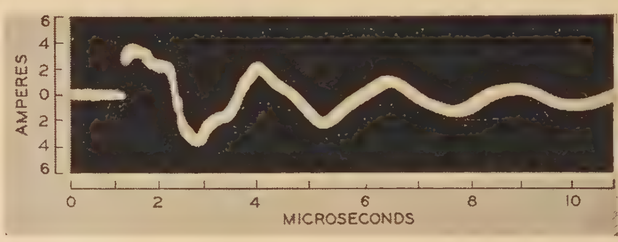


Figure 8. Initial opening and reclosure—"B" transient (current) rapid sweep

hundred closures at 30 volts, nearly every closure at 100 volts, and several for every closure at 250 volts. It is believed that the transients observed indicate the formation of minute metallic bridges[1] between the approaching contacts due to a softening of the metal by a cold point discharge and its deformation by the static field, and that once formed they are exploded by the discharge of current from the relay structure and adjacent wiring. The high fields necessary for phenomena of this type are of course due to the minute distances as the contacts approach final closure. A good deal of the erosion on telegraph-relay contacts operating on capacitative loads or shunted by resistance-capacity "spark-killer" circuits is probably due to these "preclosures," but they are not thought to be of much importance at the lower

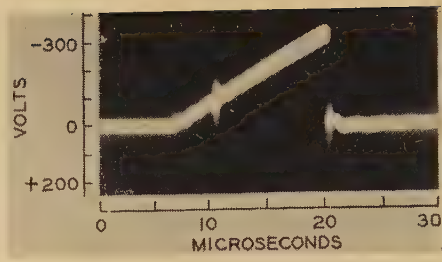


Figure 9. Evidence of point discharge (voltage)

battery voltages of the telephone plant.

Having now described the phenomena as contacts close in a doubtless oversimplified manner, we may consider that they have been closed for a long time, the direct current and the magnetic field of the load relay are established, and the contacts are to be separated. The action now becomes really complicated and much of it is as yet only surmised. Several different things may happen, and these are influenced by humidity, dirt, surface films, absorbed gases, and many other factors, including the speed of contact separation, the roughness of the surfaces, and the presence or absence of a wiping motion as well as the physical properties of the contact materials.

If the steady current exceeds certain well-known values ranging between 0.4 ampere and 1 ampere, characteristic of the contact materials, a metallic arc is formed as the contacts separate.[2] This is maintained at an initial potential of about 15 volts, and increases to a final value usually below 30 volts. The arc may last several milliseconds, but when it breaks it is followed by a complex transient lasting possibly another millisecond. These transients may be of two general types to be described later. This case is not of much importance in the telephone plant as the steady current is ordinarily kept below the value at which prolonged arcing occurs.

Metallic arcs lasting several ten-thousandths of a second, and also followed by complex transients, may occur in breaking steady currents considerably less than those ordinarily believed to cause arcing. The effect of these transient

1. For all numbered references, see list at end of paper.

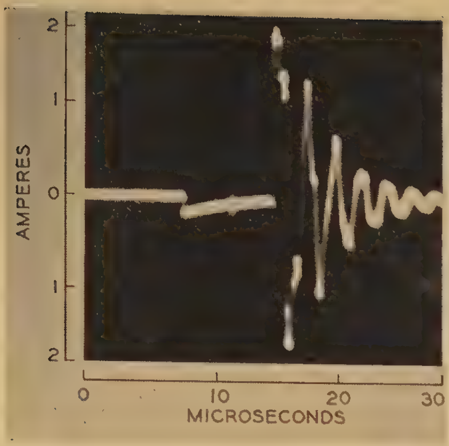


Figure 10. Evidence of point discharge (current)

arcs on contact life has not been studied separately, but they can hardly fail to increase the erosion. Their effect is unavoidably included in the studies of contact life in the higher range of d-c values. Figure 2 shows the voltage between a pair of opening silver contacts in which the steady current (0.25 ampere) is strong enough so that a brief metallic arc (indicated by the upward deflection of the trace to a new horizontal position) precedes the final transient.

If the steady-state current is low enough so that neither prolonged nor brief metallic arcs are formed at the initial contact separation, one of two general types of complex transients occur, or both types may be mixed. These have been designated the *A* and *B* types. The *B* type transient seems to be the more normal and it is difficult, probably impossible, to set circuit and contact conditions which will never give a *B* transient. It is identified by a bright spark between the contacts, showing in a spectroscope bright lines of the vaporized metal, and consists of a series of disruptive spark-overs at gradually increasing voltages. Each spark-over is individually very complicated. The appearance of the contacts during the *A* type transient is radically different from that during the *B* transient. There will be a minute bright spark, surrounded by a violet cloud which spreads out from the immediate contact area over the negative contact, and sometimes travels as far as a sixteenth of an inch from the working area.

As a result of thousands of observations of the transient currents and voltages, and many experiments, and discussions with several physicists and engineers with whom the writer is associated, a plausible explanation of the phenomena has been arrived at and will be given as at least a working hypothesis.

The voltage wave form of an entire *B* transient, covering the time from the initial separation of the contacts to the final subsidence of the voltage charging the line wire is shown in figure 3, and the a-c components of the current in the range from 20 kilocycles to 20 megacycles are shown in figure 4. The low-frequency components of the current are comparatively weak. A line and load relay were chosen to give a relatively simple transient with the important components at frequencies which could be photographed. A 500-ohm Western Electric U-type relay and a line of 300 feet of number 22 switchboard pair were used. The mate wire of the pair was grounded at both ends. The currents and voltages were not photographed simultaneously but the types of the transients were correlated by repeated observations. A current picture will not exactly correspond to a voltage picture, as the transients produced by successive operations of a contact are never identical.

The *B* transient may be explained as follows, using as a basis the simple circuit of figure 1. The steady current is established and the contacts start to separate, moving apart at a speed, which is at first surprisingly slow (about an inch a second). The contacts have been deformed by the pressure between them, and as this is relaxed, the current density and the temperature at the contacting areas rapidly increase until at some light pressure the area becomes so small that the current explodes it. There may be some necking out of the softened contacts before this and under some conditions there are indications of a metallic arc lasting a fraction of a microsecond, but at any rate, an initial rupture occurs between hot and soft metal areas.

The wire has been at ground potential, but the battery plus the collapsing magnetic field of the load relay commence to charge it at a rate depending on the line and relay-winding capacity and the relay inductance and losses. In 10 or 20 microseconds, it has reached at the contacts a potential of from 50 to 200 volts. This is below the voltage at which spark-over due to ionization of the air can occur, but something usually happens which recloses the circuit. This is believed to be caused in somewhat the same manner as the "preclosures" mentioned earlier. It is probable that a cold point discharge reheats the contacts. This is followed by a collapse of the voltage to about 15 volts above zero in the direction of the previous voltage, indicating the formation of a metallic arc. This lasts a fraction of a microsecond and the voltage then drops to nearly zero, suggesting that the contact areas heated by the field current and the arc have been drawn together in solid metallic contact. The line is discharged with an oscillation of comparatively low damping (which is characteristic of the line wire) reaching a current peak usually ranging from 0.5 to 2 amperes. The first cycle of the oscillation is distorted by the higher resistance of the path to ground caused by the arcing stage in the reclosure. After a few microseconds the

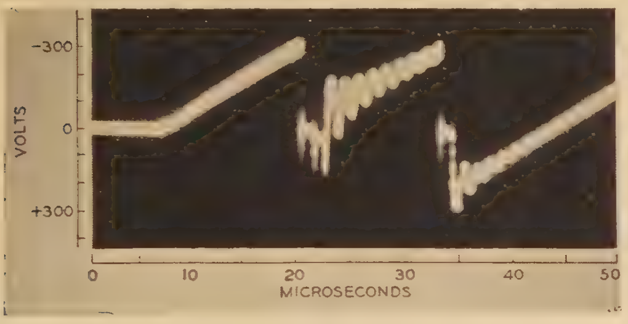


Figure 11. Early part of "B" transient (voltage)

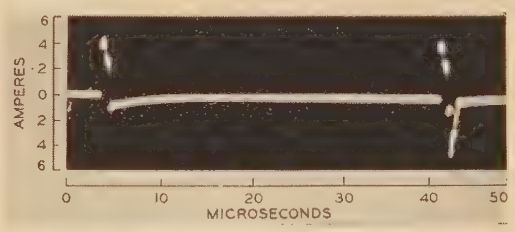


Figure 12 (right). Early part of "B" transient (current)

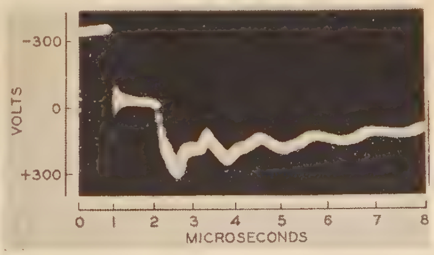


Figure 13. Single spark-over of "B" transient with single arc (voltage)

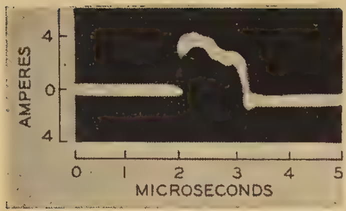


Figure 14. Single spark-over of "B" transient, with single arc (current)

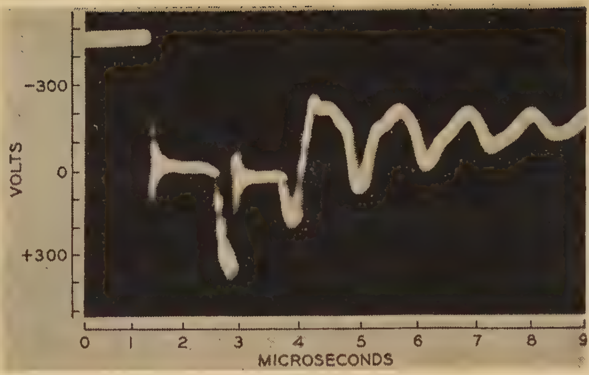


Figure 15. Single spark-over of "B" transient, with double arc (voltage)

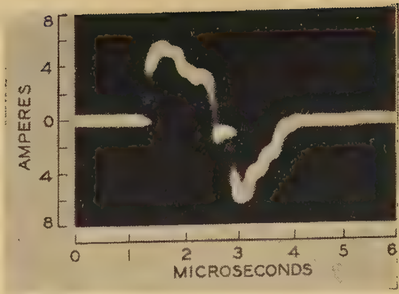


Figure 16. Single spark-over of "B" transient, with double arc (current)

contacts are opened a second time by the continued motion. Occasionally they reclose a second time but they usually stay open until the voltage has built up by the continued discharge of the load relay inductance to a value between 300 and 350 volts. Then a spark occurs at what is usually considered the minimum sparking potential between contacts in air.

Figures 5 and 6 show the voltage and current of the initial opening and reclosure of the contacts at the start of a *B* transient. The brief arc at initial opening is barely detectable in figure 5. Figures 7 and 8 show similar voltages and currents at an increased sweep speed. In figure 7 the metallic arc established during the reclosure is plainly evidenced by the collapse of the voltage to about 15 volts and its maintenance at this value for about a microsecond before it drops to zero. The effect of the arc in distorting the oscillating discharge of the current from the line wire is evident in figure 8. The current oscillation of figure 8 may be duplicated merely by charging the line wire to a suitable voltage through a high resistance and closing the contacts, the far end of the line being grounded through the load relay and a large capacitor which replaces the usual battery.

It is likely that the point discharge precedes the arc on reclosure by such a short time that it cannot ordinarily be resolved. Nevertheless disturbances of the voltage and current are occasionally found which seem to indicate that a discharge path formed and was checked (possibly by melting off the point) without establishing an arc or metallic bridge. Such a disturbance of the rising voltage is indicated in figure 9 by a high-frequency oscillation about five microseconds after the first rise of the voltage trace. Figure 10, which shows the current of the second of two initial reclosures, indicates a similar phenomenon. Five microseconds after the rupture of the circuit, shown by the downward deflection of the zero line, a dim line upward records a current surge lasting a fraction of a microsecond and reaching about three-fourths ampere. This surge however did not result in the immediate formation of an arc which was established about five microseconds later.

The initial separation of the contacts does not always result in a metallic reclosure. Figure 11 shows the voltage of the early part of the *B* transient. Here the first collapse of the voltage is a spark-over from about −300 volts which establishes an arc at about −15 volts. This arc is broken and as the line is not completely discharged, the voltage between the contacts rises to about +140 volts; a second arc is established at +15 volts and broken in its turn. Possibly because of the continually increasing distance, the arc is not re-established, and the voltage builds up with oscillations of a frequency characteristic of the line wire insulated at both ends until it reaches −300 volts a second time and another spark passes. This time only one arc is formed, and the recovery of the voltage starts from the positive side of the zero axis. The current surges corresponding to the voltage collapses of figure 11 are shown in figure 12. Here the first pulse represents a spark-over which formed only one arc. As the current from the line reached about four amperes it was checked and the conducting arc was broken (possibly by being extended laterally into the region of cooler metal). The second pulse shows the current of a spark-over which formed two arcing periods.

These phenomena are shown in more detail in figures 13 and 14 which show the voltage and current of a spark-over forming only one arc, and 15 and 16 which show the wave forms when two arcs are formed. Note that the frequency of the current oscillation is that of the line grounded at one end only (the impedance of the load relay being high at this frequency) and is about half that of the voltage oscillation which is that of the line open at both ends. Oscillations of both frequencies may be found in the line at a distance from either end.

Corresponding observations may be made of the occurrence of 3, 4, and 5 arcing periods, the pattern followed being about the same. The higher the voltage at spark-over the more arcing periods;

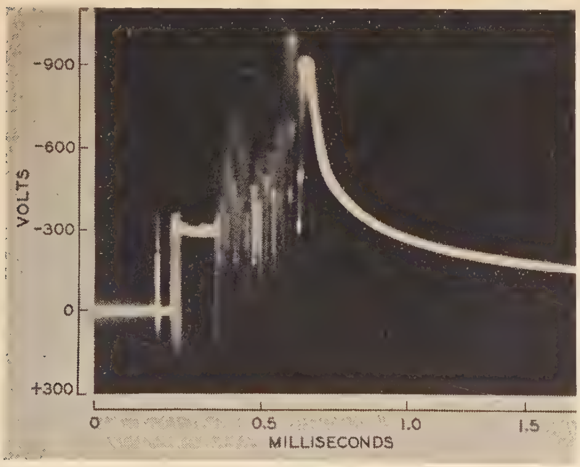


Figure 17 (left). Typical "mixed A and B" transient (voltage)

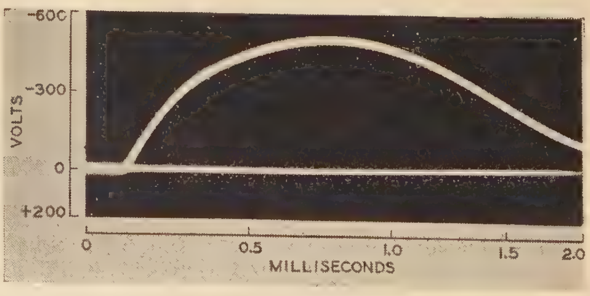


Figure 18. Effect on voltage transient of changing wire-line length—1,100 feet

an odd number of arcing periods is followed by a recovery of the voltage from the opposite side of the zero axis from that of the voltage before spark-over, an even number by recovery from the same side of the zero axis. The arcing periods are individually complex, having superposed on them oscillations believed to be due to the relay structure and the leads to the oscillograph which are too fast to be resolved photographically by the means available. These oscillations may be observed visually by using higher sweep speeds and reach frequencies of 250 megacycles.

While the arcs ordinarily do not exceed a microsecond in duration, they are probably an important factor in determining contact erosion, as several hundred may occur at each contact opening.

As may be seen from figure 3, the spark-overs continue to occur, the successive voltage breakdowns corresponding to the normal sparking potential as the contact separation increases with time (with some irregularities due to residual ionization in the gap) until the separation is finally so large that the energy remaining in the load relay cannot charge the line to the breakdown voltage. At this stage the line discharges slowly back through the load relay to the battery voltage. The peak voltage reached may be as high as 2,000 volts.

The principal characteristics of the B discharge can be produced by a simple experiment which does not use a load relay. The transient is not dependent on a load inductance, but only on a source of voltage which will charge a wire at a sufficiently rapid (but not too rapid) rate while a pair of contacts, which initially ground the wire, are separating. If a wire about 100 feet long is connected to a source of somewhat more than 350 volts through a resistance of from 5,000 to 20,000 ohms, and is also grounded by a contact at one end, a transient is produced when the contacts open which shows the characteristics of a B type transient except the final dying away of the voltage to 50 volts.

It must not be understood that every spark transient is purely of either the A or the B type. It is very common for the A type transient to break down into the B type and less often the B transient establishes the gas glow discharge for a brief period in the middle of the spark-overs.

A "mixed" transient is shown in its entire duration in figure 17. Here, after a group of spark-overs, a period in which the voltage is maintained steadily at about 300 volts for about 0.0002 second intervenes, and is followed by more spark-overs from considerably higher voltages. In order to produce this transient the length of the line wire was reduced to ten feet, at which length and with a 1,000-ohm load relay the tendency is to produce intermittent groups of A or B transients, interspersed with the mixed type shown, when the relay is operated frequently.

The number of spark-overs in each B transient varies with the circuit conditions. As many as a thousand may be found with a load consisting of a number of relays in parallel on a wire of moderate length and as few as one in the limiting case.

While the occurrence of the B transient is favored by long line wires and high-impedance relay loads, beyond a certain length which with telephone relays and wiring is from 300 to 2,000 feet (the longer lengths being associated with the lower impedance relays) no spark-overs at all occur. The voltage build-up is so slow that the spark-over potential is not reached at any time during contact opening and the contacts may be said to be protected by the line wire. The series of voltage oscillograms, figures 18 to 24 inclusive, shows the change from a smooth transient with no spark-overs through the B type with an increasing number of spark-overs to the final A type. The A type transient of figure 22, which has superposed on the 300-volt gas glow discharge stage a relaxation type of oscillation, the B transient of figure 23 and the simple A transient of figure 24, were all produced under identical conditions in quick succession. The change in characteristics from figure 18 to figure 24 was produced merely by a

Figure 19 (left). Effect on voltage transient of changing wire-line length—600 feet

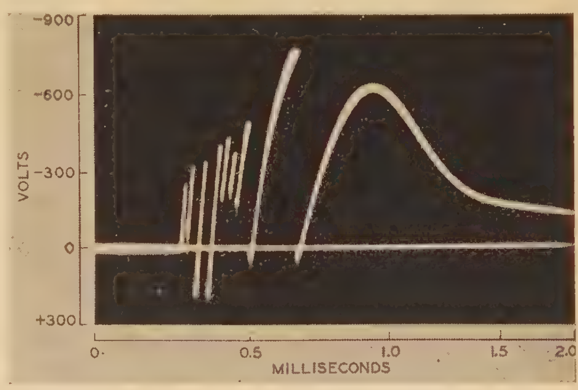


Figure 20 (right). Effect on voltage transient of changing wire-line length—150 feet

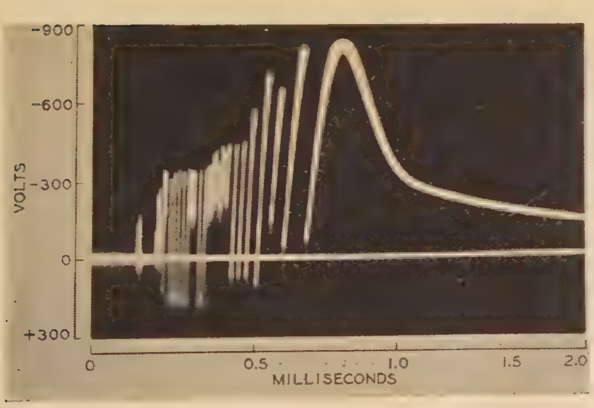


Figure 21 (left). Effect on voltage transient of changing wire-line length—50 feet

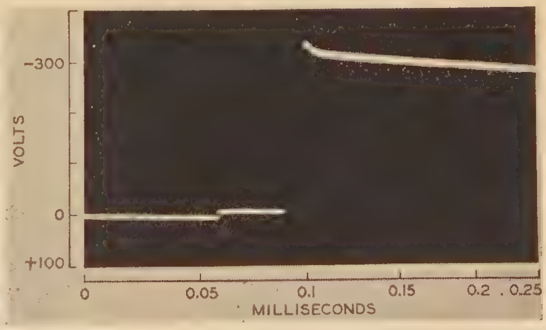


Figure 22 (right). Effect on voltage transient of changing wire-line length—10 feet

reduction in the length of the connecting wire from 1,100 feet through three intermediate stages to 10 feet, a 1,000-ohm load relay being used. This explains a puzzling effect noted with many contact

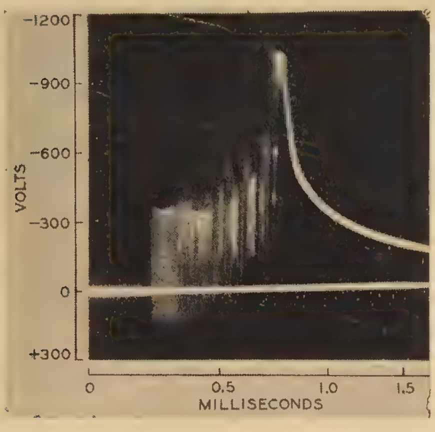


Figure 23. Effect on voltage transient of changing wire-line length—10 feet

materials. With a supposedly identical circuit, the erosion will be small with very short wires, increase rapidly as the wiring length increases, and then decrease again becoming very small with very long wires.

The *B* transient is more frequently observed with freshly filed contacts, at high humidities, and with a rolling or wiping motion of the contacts in opening. It is always found if the contacts are of oxidized metal or operate in an oxygen atmosphere. In fact, there seem to be good reasons for believing that its production is bound up with the presence of oxygen on or in the surface of the active contact metal.

It may be seen from the last series of oscillograms that if the circuit and the conditions of the contact surfaces are just right, the *B* transient is replaced by a much simpler and less stable type, the *A* transient. It will occur usually when the wiring is short or the load relay is of low impedance, with contacts which have been operated until the original surface has been burned off and have not stood idle more than a few minutes. It starts much as does the *B* type, but after a dozen or a hundred spark-overs from about 350 volts, which come much closer together in time than those of the *B* transient, the voltage becomes steady at about 300 volts. This condition lasts for perhaps 0.6 millisecond, then the voltage rises to about 400 or 450 volts and gradually reduces, reaching the battery voltage after several milliseconds. A typical *A*-type transient is shown in figure 24. It is suggested as a hypothesis that during the spark-over stage, the oxygen is being exhausted from the surfaces of the current-carrying areas of the contacts by burning the metal and that when this has been completed, a nitrogen-gas glow discharge is formed and maintained during the rest of the contact opening, if the supply of energy from the load inductance through the line is rapid enough to prevent the voltage from dropping below about 280 volts.

The glow-discharge phase of the *A* transient is unstable. If transient voltages induced by the operation of relays in other circuits reach the contact gap during the time that a sustained glow discharge is attempting to form, its formation is interfered with and a mixed or *B*-type transient results. Occasionally as illustrated in figure 22 the glow discharge of the *A* transient has superposed on it a saw-toothed oscillation of from 10 to 50 volts peak-to-peak. Part of an *A* type transient showing this peculiarity is illustrated by the oscillogram of figure 25. This appears to be a relaxation oscillation such as is commonly produced in ionized-gas tubes, riding on the normal 300-volt axis of the gas glow discharge. The conditions which lead to the occurrence of this oscillation at atmospheric pressure have not been identified, but it is found to be quite stable in some cases where contacts have been sealed in a mixture of air and gases at about half atmospheric pressure.

A typical *A* transient is shown in detail in figures 26, 27, and 28. The circuit consisted of a 250-ohm relay connected to the contacts by ten feet of wire, the battery being 50 volts as usual. Figure 26 shows the voltage of the early part of the transient during which rapid spark-overs are interspersed with two brief periods during which a gas glow discharge was established but not maintained. Figure 27 shows the final spark-over before the establishment of the glow discharge at about 300 volts. A group of the current pulses corresponding to the initial part of the spark-over stage is shown in figure 28. These are complicated by the line oscillations (which should be of about 30 megacycles frequency) and appear to last less than 0.1 microsecond.

It may be seen that the individual spark-overs at the start of the *A* transient are somewhat different in form from those of the *B* transient. The voltage reaches 320 volts in a microsecond or so, and in some cases collapses to zero or beyond immediately. There are sometimes indications of arcing periods lasting much less than 0.1 microsecond and the voltage recovers with oscillations of the line wire but the duration of the phenomenon is too brief for very accurate analysis. But in many cases, the voltage having reached its peak, drops to an intermediate value of 280 volts and recovers to 320 volts before it collapses. This is probably due to the temporary formation of the nitrogen glow discharge, which is finally established and maintained during the remainder of the contact opening when for some reason the spark-over does not occur. In cases where the contacts are on the verge of producing a *B* transient the voltage may rise to 500 volts and then collapse to the 300 volts of the gas glow discharge.

It is very interesting to set up a circuit which will cause the *A* transient to predominate, and start operating freshly filed contacts several times a second observing the transient voltage at contact opening on the oscilloscope. The first transient will always be of the *B* type. Usually the first few dozen will also. However, after a while one of the transients will show a flat top at about 300 volts for a very brief period and this tendency increases until finally a complete *A* transient occurs. After this, the *A* transients become more and more com-

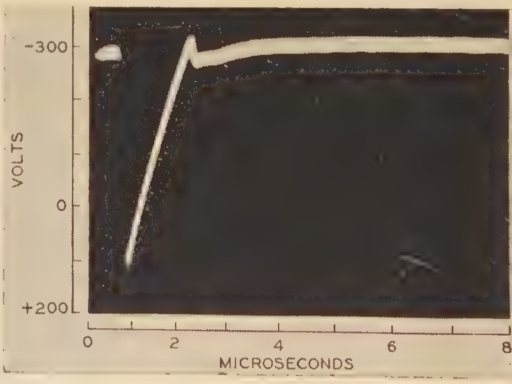


Figure 24. Effect on voltage transient of changing wire-line length—10 feet

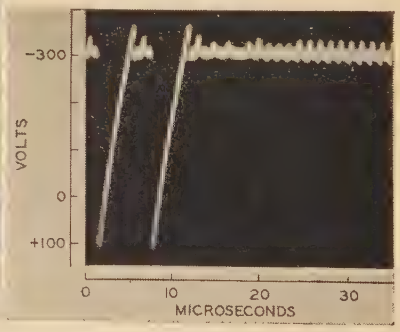


Figure 25. Oscillation on glow discharge of "A" transient (voltage)

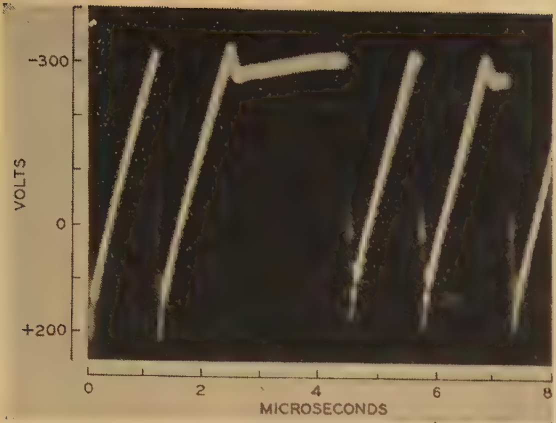


Figure 26 (left). Start of "A" transient (voltage)

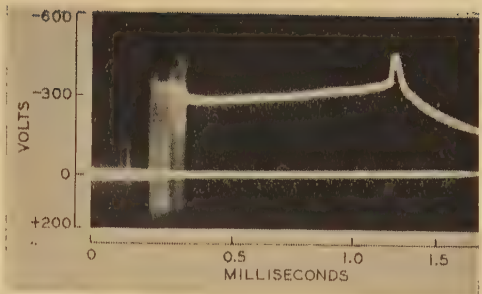


Figure 27 (right). Start of stable glow discharge of "A" transient (voltage)

mon until finally the B transients occur perhaps once in a hundred openings. If then a gentle stream of oxygen is blown on the contacts, only B transients will occur until a few seconds after it has been turned off. Blowing the breath on the contacts has a similar but less definite effect, while a stream of dry compressed air has no effect.

If on the contrary the circuit conditions are selected so that B transients predominate, a stream of nitrogen will induce A transients. That is, A transients are not found in oxygen and B transients are rare in nitrogen.

If instead of operating the contacts several times a second they are operated at longer intervals, the tendency to produce the A transient is reduced. When contacts are operated in air a certain interval between operations can be found which causes all transients to be of the B type. This probably depends on humidity and also on circuit conditions and contact material. In one experiment, a wait of 45 seconds between operations gave all B transients with silver contacts, while a wait of five minutes was required with palladium contacts. This is possibly due to a different rate of film formation.

Life tests on palladium contacts show much lower erosion with A transients than with B transients. The effect of the two types of transient in terminating the life of silver contacts is not markedly different. The contours of the eroded surfaces exhibit a wide variety, and it is not easy to correlate the transient type with its effect. It is evident, however, that areas of the contacts which have never been in the d-c path may be severely eroded.

When we consider that the B transients produce oscillations in the line wires reaching several hundred volts and often 15 amperes, it is not to be wondered at that clicks will be produced in circuits in the immediate neighborhood of unprotected relay contacts. The A transients produce much weaker currents than the B transients and many contacts on successive operations will produce A, B, or mixed types. This explains the common observation that relay clicks vary over a wide range of amplitudes. The arrangement of telephone circuits in which the cabled wiring always contains a large number of grounded conductors, and is often enclosed in a lead shield, prevents any appreciable free radiation of the spark transient oscillations.

With the foregoing information available the contact erosion process at opening contacts appears briefly to be as follows. At very minute separations high field strengths exist even for moderate voltages. The resulting cold point discharge is often followed by a metallic arc which softens a tiny point on the contact which is pulled out and fused into metallic contact under the action of the high fields. After rupture by increasing separation or increasing current density, the process may repeat or, as is more likely, the separation is too great for another metallic bridge to form. The high field discharge then sets the stage for the next type of conduction or breakdown. This may be either a series of spark-overs interspersed with metallic arcs of extremely short duration or a gas glow discharge, initially intermittent and then more or less stable. Factors predisposing toward one or the other type of discharge are known thus far only in a most general fashion and much remains to be done before the relation between contact erosion and the transient currents and voltages can be predicted accurately. There is ample evidence that molten metal may be expelled from the immediate contact area at high velocity and may be deposited at distances of at least 0.1 inch. It also appears that both the ionized nitrogen cloud of the A transient and the disruptive sparks of the B transient may corrode the contacts and their supports at locations and distances which never enter directly into the rupture of the current path.

We have seen that the line wire contributes to the current surges through contacts due to its properties as an oscillatory circuit, charged repeatedly by the energy stored in the magnetic field of the relay. The surges and the resultant erosion may be reduced in several ways. If a radio-frequency choke coil is connected between the contact and the line wire, the discharges of the latter are much reduced, and the A type gas glow transient favored. A group of many current surges of 15 amperes peak may in most cases be reduced to one or two of 0.15 ampere or less, and a radical reduction in erosion secured. Unfortunately choke coils are expensive and inconvenient. The usual line wire may be terminated in approximately its surge impedance by shunting both ends to ground with a resistance of about 100 ohms in series with a capacitor of the order of 0.01 microfarad. This heavily damps the line oscillations and greatly reduces the number and severity of the current surges. It is also expensive. Instead of the copper line wire, a material such as iron or Permalloy-plated copper having a high surge impedance and large high-frequency a-c losses may be used. This seems more practical, but brings up new problems in design, handling, and soldering.

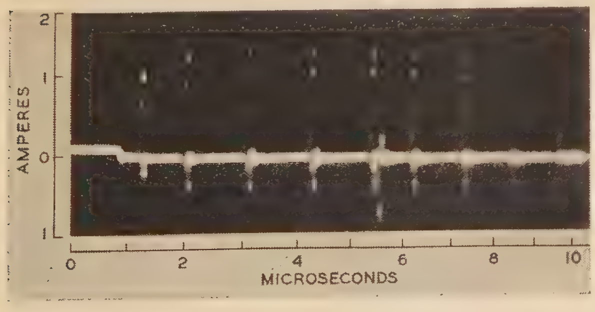


Figure 28. Start of "A" transient (current)

The most effective means of reducing erosion is of course the well-known "spark-killer" (consisting of a capacitor and resistance in series, shunted across the contact or load), which can be designed to hold the voltage below the spark-over point at least until the contacts have separated a safe distance.

When the conventional spark-killer is used it is generally assumed that what sparking then occurs is due to the discharge of the capacitor when the contacts close, provided that the spark-killer prevents the voltage at contact opening from reaching 350 volts. Unfortunately the "reclosure" effect described earlier appears unless the initial rise of voltage as the contacts separate is held down to a value considerably below the sparking potential by a suitable choice of the resistance in series with the spark-killer capacitor. If the rate of increase of the initial voltage in relation to the speed of separation of the contacts exceeds a figure which seems to depend on the contact material and the condition of its surfaces, the high-field point discharge comes into play and causes the separating contacts to reclose metallically while they are still at a minute separation and moving apart very slowly. In "reclosing" the line wire and capacitor are discharged, the current explodes the minute metallic bridge, producing a visible spark, and the circuit is thus reopened. This may occur a dozen times in some cases before the contacts finally stay separated. The higher the voltage which the spark-killer permits the more likely are the reclosures to take place, and the larger the number of reclosures at each contact opening. However, reclosures are usually not very common in cases where the voltage of the wave front is held below 50 volts. In the majority of cases in the telephone plant it is possible to do this without incurring much of a penalty due to erosion of the contacts on closing by the discharge of the spark-killer capacitor.

This discussion is not more than sufficient to serve as an introduction to the problems of contact sparking as revealed by the improved observing technique used in this study. Only the simplest cases have been considered, and the telephone plant is far from being simple. Many relays have multiple windings or metal sleeves, and multiple connections to the contacts are very common. As these complications considerably modify the contact spark wave form and erosion, each contact with associated circuits presents its own problem. The solution of these problems involves the careful study of circuit characteristics of a type which are ordinarily left to the radio engineer, as well as of the mechanical, chemical, and metallurgical properties of the contact materials.

References

1. The Formation of Metallic Bridges Between Separated Contacts, G. L. Pearson. *Physical Review*, volume 56, September 1, 1939, pages 471–4.

2. Minimal Arcing Current of Contacts, H. E. Ives. Franklin Institute *Journal*, October 1924.

Discussion

E. E. George (Phoenix Engineering Corporation, New York, N. Y.): The paper under discussion contains considerable material of a fundamental nature. This subject apparently has not been discussed previously before the AIEE. The paper answers many questions but raises many more and it is to be hoped that further work on the same subject will be published in the future.

Various relay engineers working with high-speed relays or with long cable circuits for pilot-wire protection or remote control, have run into numerous difficulties resulting from transient phenomena. It would be interesting to know whether the author has found any effect on relay operation other than contact deterioration. It seems that sensitive high-speed telegraphic relays should be affected by the transient currents observed by the author. In power-relay practice, a neon lamp with a high series resistance is frequently shunted across open relay contacts to act as a circuit monitoring device. It would be interesting to know the effect of this lamp on contact operation. It would also be interesting to know whether there is a critical maximum battery supply voltage or length of circuit beyond which trouble is likely to be experienced on pilot-wire circuits.

This paper may explain some of the difficulties frequently observed in trying to use very small d-c supervisory currents on pilot-wire circuits—currents under ten milliamperes.

The author makes reference to so-called "spark-killer circuits" consisting of a capacitor and series resistance, and it would be helpful to give some formula or basis for selecting the proper values of capacity and resistance for such circuits. In the past, it has been the practice of most engineers to consider contact operation perfect if there were no visible sparking. The author has contributed much to a better understanding of contact operation and his paper might well be required reading for all relay engineers.

A. M. Curtis: The principal effect of contact sparking transients aside from erosion is in causing contact sticking and consequent failure of the relay to open its circuit. It is possible to conceive of circuit conditions where the cross fire from a lead through which the steady current and transients of a telephone-type relay flows might cause brief operations of a very sensitive relay connected to another lead in the same cable. The principal difficulty from the contact sparking transients would be expected in cases where the induced currents reached the sensitive relay through a rectifier and particularly if the latter should be of a type where the very strong but very brief induced currents might be stored and discharged more slowly. It is hard to make a mechanical relay operate on a pulse only a thousandth of a second long.

A neon lamp shunted across relay contacts gives considerable protection, particularly if the series resistance is not too high. However, this is not as good as a proper spark capacitor as the delay in breakdown of the gas lamp may be 50 to 100 microseconds. During this period the voltage between contacts usually rises high enough to permit several spark-overs.

There is a complicated relation between contact material and battery voltage which has an important influence on the performance of contacts, especially those which work into capacity loads or are protected by capacity spark-killers. Generally it pays to keep the voltage low. Many contact materials which work well between 25 and 50 volts will be unsatisfactory at 150 volts.

I do not know of any general formula which can be used to design spark-killers. They fall into two general classes and some simple guiding principles can be stated.

If the steady current through the contact is above the arcing current of the material it is desirable to keep the voltage at the first opening of the contacts below the arcing voltage. This indicates about as large a capacitor as can be afforded and a resistance at least as low as $R=10/I$. But this leads to a situation where the discharge of the capacitor through the closing contacts may do more damage than the arc which is prevented and a compromise must be made by increasing the resistance to a value where the transient arc is no more troublesome than the capacitor discharge. This, of course, depends on the battery voltage and is another reason for keeping it low.

If the steady current is below the arcing value for the contact materials, the resistance for the best performance should be high enough to prevent the capacitor discharge currents through the closing contacts exceeding about one-third ampere, and low enough to limit the voltage at first instant of contact opening to about 50 volts. That is, it should be higher than $R=3E$ and lower than $R=50/I$. The first condition guards against explosive reopening of the contacts at closure; the second avoids reclosures on opening (always assuming a sufficiently large capacitor). But at the higher battery voltages and currents it is not possible to meet both conditions and in these cases a compromise must be again made. The capacitor should be large enough to keep the surge voltage from reaching 300 volts until after the contacts have separated about 0.002 inch. With many relays this takes about a quarter of a millisecond after the contacts have first started to separate. The capacity required varies with the relay. With a high-resistance relay 0.1 microfarad may be enough. One microfarad is enough for the general run of telephone relays but some heavy-duty electromagnets may require several microfarads.

450 MILES OF ROTATED TOWER LINE

THE TWIN 230 K.V. transmission line from Vancouver to the Bonneville Dam is here shown on its side-hill descent of Larch Mountain, and continuing on through a swath in the forested river bottom to Bonneville Dam, a glimmering band of white in the background. The Columbia River may be seen pursuing its rambling course at the foot of the distant hills.

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These towers are designed for extra heavy lines with especial consideration given to the character of widely variant and often hazardous topography. And, as usual in American Bridge practice, full size specimens have undergone the "acid test" in our Shiffler Plant test frame, where field loading conditions conforming to the specified design criteria were duplicated.

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Industrial Notes

Expansion Programs.—Work will start this month on a new building and additions to present structures of the Westinghouse Mansfield, Ohio works. The cost will exceed $500,000 for building and equipment which will increase the production capacity of household refrigerators by one-third. . . . . A new building for the plastics department of the General Electric Co., at Pittsfield, Mass., costing $50,000, will be completed this month. The structure will be used for the development of new plastics on a small production basis. . . . . .The International Nickel Co. has approved plans for the improvement of its Huntington, West Va. plant, costing $132,000. An additional car-type, electric heat treating furnace is included among the new equipment to be installed. . . . . .The Gibson Electric Co., manufacturers of electrical contacts for use on circuit opening and closing devices, has purchased and now occupies a modern 3-story plant at 8344 Frankstown Ave., Pittsburgh, Pa., which will greatly increase previous production capacity. . . . . .Construction of a new factory has been started by G-M Laboratories, Inc., Chicago, manufacturers of scientific electrical instruments, control apparatus, magnetic relays, photoelectric cells and other equipment. The company was organized in 1925; officers are A. J. McMaster, president and C. E. Parson, vice-president.

Roller-Smith Adds Plant.—The Roller-Smith Co., Bethlehem, Pa., has transferred its switchboard division to a recently acquired plant in Allentown, Pa., which is now in full operation, according to Joseph D. Wood, president. The air and oil circuit breaker and instrument divisions will remain in Bethlehem. The switchgear division has its own engineering, drafting and assembly departments in the new plant, of which J. E. Bevan is manager. W. S. Swoish, the company's sales manager, will also supervise sales of the Allentown division. Mr. Wilfred A. Clabault, formerly with the Westinghouse advertising department, has been appointed advertising manager of the company, and will also be engaged in sales.

Appointments and Promotions.—A. B. Chance is now chairman of the board of the A. B. Chance Co., Centralia, Mo.; F. G. Chance has been elected president; N. A. Toalson, vice-president; J. T. Isbell has been made vice-president in charge of sales, and O. E. Walker, vice-president in charge of production. . . . . .Wilson K. Winbigler is in charge of the new Baltimore branch office of the Ward Leonard Electric Co., of Mt. Vernon, N. Y. The office is located in the Hearst Tower Building. . . . . .G. E. Hunt has been appointed manager of the Cutler-Hammer, Inc., Indianapolis office, at 307 N. Pennsylvania Ave., and O. P. Robinson has been added to the sales engineering staff of the Pittsburgh office. . . . .Chester H. Lang, manager of General Electric's advertising and sales promotion activities since 1932, has been named manager of apparatus sales and vice-chairman of the company's apparatus sales committee. He is succeeded by Robert S. Peare, president and general manager of the Maqua Co., a large printing and engraving concern affiliated with the General Electric Co., at Schenectady. He will also be responsible for the operation of the G-E broadcasting stations. . . . . .J. G. Gidley is now manager of sales of General Electric Schenectady section, turbine division. . . .Don J. Murray has been appointed sales manager for General Electric conduit products, and H. K. Smith has been made manager of distribution services and secretary of the distribution committee of the appliance and merchandise department, Bridgeport, Conn.

Eisler Now Callite Tungsten Corporation.—The corporate title of the Eisler Electric Corporation, Union City, N. J., has been changed to Callite Tungsten Corporation. The company serves many industries with both materials and equipment for the manufacture of incandescent lamps, neon signs, radio tubes, and other electronic devices, as well as electrical contacts of all types. It has specialized in refractory metals and other alloys, particularly tungsten and molybdenum in the form of rod, sheet, wire, and special shapes.

Trade Literature

Resistors.—Catalog 40, 12 pp. Describes vitreous enameled resistors and rheostats in all ranges; prices are included. Hardwick-Hindle, Inc., Newark, N. J.

Gear Motors.—Bulletins 403 and 404. Describe single, double, and triple reduction a-c and d-c gearmotors. Reliance Electric & Engineering Co., Cleveland, Ohio.

Relays.—Catalog 7, 24 pp. Describes an extensive line of a-c and d-c relays and solenoids. Relay types include transmitter, overload, time-delay, interlocking, mercury-contact, counting unit, etc. Guardian Electric Mfg. Co., 1622 W. Walnut St., Chicago.

Transformers.—Cat. Sec. 44-100, 16 pp. Describes a complete line of dry type transformers, auto-transformers, boosters, and phase changing transformers from 1 to 50 kva, for application where space limitations and insurance regulations prohibit the use of oil insulated apparatus. Westinghouse Electric & Mfg. Co., East Pittsburgh, Pa.

Product Directory.—Bulletin B6057, 32 pp. Lists 1,610 different and widely diversified products, including descriptive engineering literature and bulletins available on 280 power, electrical, and industrial machines. Manufacturing plants in seven states are illustrated and district offices in the United States and abroad are listed. Allis-Chalmers Mfg. Co., Milwaukee, Wis.

Fire Protection Systems.—Bulletin F-11. A comprehensive description of built-in and mobile carbon-dioxide fire extinguishing equipment especially applicable to electrical apparatus. Tests on transformer oil fires are illustrated. A typical protection layout of a generating station is included. Cardox Corp., 307 N. Michigan, Chicago, Ill.

Voltage Regulators.—Bulletin GES-2285, 8 pp. Describes type AIRS voltage regulators, built in ratings from 1.2 to 12 kva, 60 cycles, single phase, and from 120 to 600 volts; available for automatic, manual, and manually controlled motor operation. Lists specific applications and advantages accruing from installations. General Electric Co., Schenectady, N. Y.

Receiving Tubes.—Bulletin 1275B, 12 pp. Charts give characteristics data on all glass, glass-octal, octalox and metal types of receiving tubes in numerical and alphabetical order. Classification of the types according to their cathode voltages and their functions are included, as well as socket connections with RMA designations. Commercial Engg. Sec., RCA Manufacturing Co., Harrison, N. J.

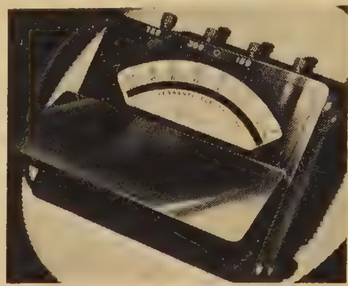
New Products

Electric Current Visualizers.—Devices recently patented by W. W. Geiser, 4630 N. 11th St., Philadelphia, Pa., show visually, by simulation, both alternating and continuous currents flowing through the windings of the principal types of rotating machines. Three types are available for classroom use, representing a two-phase alternator, a two-phase squirrel cage induction motor, and a four-pole continuous current interpole generator. They are approximately $16\frac{1}{2}$ inches high, $13\frac{1}{2}$ inches wide, and 8 inches deep, with driving motor and lighting self-contained. The transparent dial of each type shows a sort of phantom picture of both stationary and revolving parts, while the current flows realistically through the windings in the proper direction. In addition to the flow of current, some of the phenomena which may be seen includes, in the continuous type (illustrated)

operation of a plain compound wound generator; sparking of the brushes, when moved out of their neutral position, and the cause; shifting of the magnetism, with an increase in the number of lines representing an increased load, and its effect upon commutation; the cause of armature reaction; the introduction of inter-poles and their effect. For synchronous or induction machines the appropriate visualizers are equally effective. For individual use, the three types are reduced to pocket size. They may be held before any source of light and all phenomena studied at the convenience of the student, as slowly as he cares to operate the devices by hand.

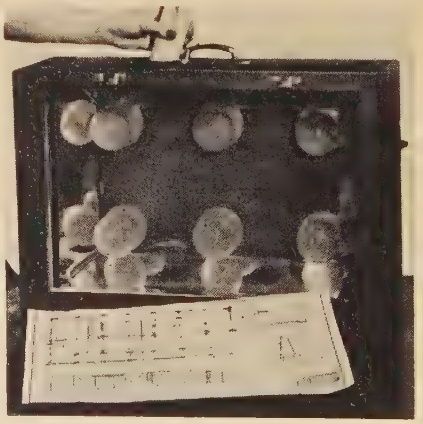
Slot Insulation.—A new combination slot insulation, made from 100 per cent rag paper combined with Vartex black bias varnished cloth by a special adhesive, has recently been introduced by the New Jersey Wood Finishing Co., Inc., Woodbridge, N. J. This combination slot insulation, termed "Varslot", has unusual flexibility and is highly resistant to moisture and lubricating oils. With greater tearing strength in both directions, the material will stand abuse and will not buckle when placed in a slot. Due to its unusual flexibility, the dielectric strength is not reduced by normal bending and the slot insulation can be cut, slit, or punched without difficulty. It is available in sheet form, continuous length rolls, piece or tape form in any thickness from .012 to 0.26 inch.

Portable Voltmeter.—A new triple range portable voltmeter for industrial and central station use, as well as for all service and



field testing work, has been introduced by Ferranti Electric, Inc., 30 Rockefeller Plaza, New York City. The instrument has been designed for use on a-c circuits and may be employed on d-c circuits with only a slight sacrifice in accuracy. Features of the instrument include—scale length of $5\frac{1}{4}$ inches; well lighted dial, knife-edged pointer; entirely self-contained; low-priced. Ranges: 0–150/300/750 volts; accurate to $\frac{1}{2}$ of 1 per cent; conforms to AIEE and NEMA standards and government specifications. The meter is enclosed in a polished black walnut case, fitted with a hinged cover and heavy carrying strap.

Portable Printer.—This "Elpro" portable printer, manufactured by the Ozalid Corporation, Johnson City, N. Y., has been developed for applications where prints are required occasionally. It will make positive type reproductions, in sizes up to 12 by 18 inches, of engineering drawings, maps, letters, reports, and in fact any pencil or ink lines, typewritten or printed matter appearing on one side of a reasonably translucent material. Exposure is accomplished by six specially designed lamps totaling 800 watts. The equipment operates on an ordinary lighting circuit, 110 volts a-c or d-c. A time release switch allows the operator to automatically regulate exposure. The printing operation requires from two to three minutes depending upon the type of original used, and dry development takes between three and five minutes. As many as eight prints can be developed simultaneously.



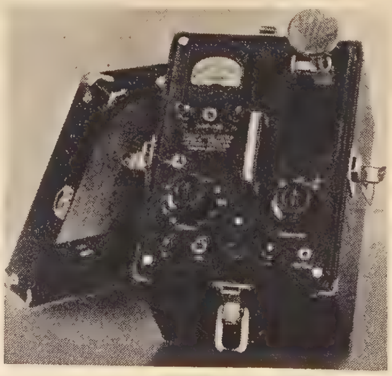
(*Continued on page 14*)

New Products

(*Continued from page 12*)

Pressure Pads for Brushes.—To offset the injurious effects of vibration on carbon brushes a resilient pressure pad secured to the holder end at the point of contact with the pressure finger has been made available by the National Carbon Co., Inc., Cleveland, Ohio. The use of these pads, where vibration of great severity is encountered, materially reduces and may even eliminate such destructive effects as chipping and cracking of brushes, wear on the holder end of the brush and wear of the pressure fingertip. The resilient material used for these pads is very durable. Within the range of temperatures normally encountered in electrical equipment the pad will retain its resiliency throughout the life of the brush. The form of the pad and its exact location on the brush are dependent on the shape and dimensions of the pressure finger and the location of its contact with the brush. The style illustrated is adapted to a wide range of brush holder designs.

Sound-Level Meter.—The type 759-B sound-level meter introduced by the General Radio Co., Cambridge, Mass., is an improved model of the older type 759-A. The new instrument meets the standard specifications for sound-level meters as adopted by the American Standards Association and various engineering societies. It is suitable for use in noise surveys, and for measuring the noise generated by machines and appliances. Features of the new instrument are accuracy, rugged construction, convenience in operation, and portability. A two-speed indicating meter with selector switch is provided. In the FAST position of the switch, the meter speed conforms to ASA specifications. In the SLOW position, the meter is heavily damped and can be used for measuring the average value of rapidly fluctuating sounds. New types of vacuum tubes and batteries give reliable operation and long life. The entire assembly is mounted in portable, airplane-luggage type of case. Batteries are self-contained. The range of the sound-level meter is +24 to +140 db.



Paper-Insulated Cable.—A new type of paper-insulated high voltage cable introduced by the Phelps-Dodge Copper Products Corp., New York, utilizes an improved insulation designed to give the oil impregnated cable longer service life, high impulse strength, and better operating performance. In this cable, known as "Titebilt", a new principle in the design of the layers of paper is employed which eliminates the formation of voids. A carefully chosen proportion of stronger, more highly elastic paper is used for the outer portion of the concentrically applied paper tapes. A means is thus provided of applying a compressing force to the more highly stressed interior of the insulation at precisely the time it is needed, that is, during contraction of the insulation during the cooling phase of its daily heat cycle. The new cables have been under test at the company's laboratories for over five years.

Test Set.—The Simpson Electric Co., 5216 W. Kinzie, Chicago, Ill., has introduced a new kit-set, consisting of three small matched meters, in a carrying case. This set is an outgrowth of a new line of nine "Micro-Testers" and is available in combinations to measure current, voltage and

resistance for practically any requirement. This grouping of individual meters provides, besides greater flexibility and low cost, much easier reading, according to the manufacturer. Measurements are recorded on separate dials, so that readings can be taken more quickly and with less chance of error than on a single dial, multiple-scale instrument. Any one of the meters may be used separately, or, if necessary, can be replaced. They are not designed to replace panel instruments in production testing, but should be useful for supplementary and portable work. The featured instrument of the new line is "Micro-Tester" model No. 280, a multiple-range a-c ammeter, which is said to mark the first time a current transformer and an indicating instrument have been combined in a small, inexpensive meter; ranges: 0–1, 0–2.5, 0–5, 0–10, and 0–25 amperes.

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¶ Limited quantities of pamphlet copies of the technical papers listed, representing surplus stock remaining from recent AIEE conventions and District meetings, are still available.

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Professional Engineering Directory

Employment Bulletin

Engineering Societies Employment Service

MAINTAINED for their members by the national societies of civil, mining, mechanical, and electrical engineers, in co-operation with other organizations. An inquiry to any of the three offices will bring full information.

A weekly bulletin of engineering positions open is available to members of the co-operating societies at a subscription of $3 per quarter or $10 per annum, payable in advance.

In the interest of effective service, it is essential that members using the employment service keep the bureau office serving them advised at reasonable intervals concerning their availability for employment, concerning any change in status, and immediately upon acceptance of any employment.

Employers interested in the following announcements should address replies to the key numbers indicated, and mail to the New York office.

Men Available

ELEC ENGR, Fellow AIEE, professional license varied util, indus exper, U.S. and abroad. Past 15 yrs chief engr, gen supt, util in Mississippi Valley; exper in continuing property records. E-647.

B.S.E.E., Tufts College Engg School, 1940; 24, single; some exper in radio engg. Radio amateur. Desires pos in oprn engg in coms. Location unimportant. Available June, 1940. E-648.

B.S.E.E.; 3 yrs Law, Night, eligible Bar many states; 28, married; 6 yrs pub util comm exper, rates, contracts, valuations, financial, depreciation and cost studies, oprtg problems, regulatory procedure. E-649.

ELEC ENGR, 18 yrs exper des, mfg, sales rotating elec machy. Chief engr several cos. Can handle engg mfg, application and sales. Seeks exec pos in elec or mech industry. E-650.

B.S.E.E., Univ of Utah, 1939; honors, Tau Beta Pi; 25, single; 2 yrs teaching asst physics lab. Desires pos with opportunity for advancement in des or research. Location, salary secondary. E-651-326-Chicago.

E.E., R.P.I., 1928; licensed prof engr, N. Y. 8 yrs coms; 4 yrs X-ray and high voltage rectifiers. Des pos in devpmt or production. Location, New York Metropolitan Area. E-652.

M.S. in E.E., Univ of Minn, 1938; 33, married; 18 mos exper pub util, asst to gen mgr; teaching exper; surveying exper; desires pos with engg future; now employed. E-653-261-Chicago.

B.S.E.E., Col City of New York, recent grad; single. Desires pos with mfr of elec or mech prod. Location immaterial, salary secondary. Available immed. E-654.

INDUS ENGR, 42, married; routing, planning, time study, wage incentive, estimating, mfg, estimating costs. Capable exec, elec and mech. Now employed. E-655.

A.B., E.E., Stanford, 1931, 1933; married; 6 yrs G.E. training including test, generator constr, sales analysis; sales exper including meters, instruments, cables. Desires pos util co, sales or engg, in West. Available immed. E-656.

SM, M.I.T., 1939; B.S.E.E., Univ. of Mich, 1936; 24, married; 2 yrs testg engr high voltage ab; 6 mos research, electronic prod. Desires pos research or des engr in high voltage engg, electronics, com. Available immed. E-657.

B.E.E.; 30, married; employed in meter dept, util co; 5 yrs exper util, steel mill, draftg, office; util co or mfg pos desired; midwest preferred; Professional Elec Engr, Ohio. E-658.

E.E., SB and SM, M.I.T., 1924; 41, married; 6 yrs tel; 8 yrs des and production engg, mfg; 10 mos state public works; elec des USHA project. Professional license, Conn. E-659.

RECENT GRAD, elec and mech engr; 28, single, ambitious. Desires opportunity for exper leading to responsible engg pos. Interested in sales and production. E-660.

B.S.E.E., W.P.I., 1935; 27, single; 5 yrs prod, inspection, devpmt, leading mfg co. Special studies in sound, vibration. Location, East or N.E. Salary secondary to work with interest and future. E-661.

ELEC GRAD, Pratt Inst, 1934, with some exper in air conditioning eqpt, install and maintenance. Desires pos in same, preferably in East. Available immed. E-662.

B.S.E.E., 1930. Util engg, indus engg and constr, mining electrification and electrician. Interested in connection util, indus organization or mining co. Available short notice. Free to travel. E-663.

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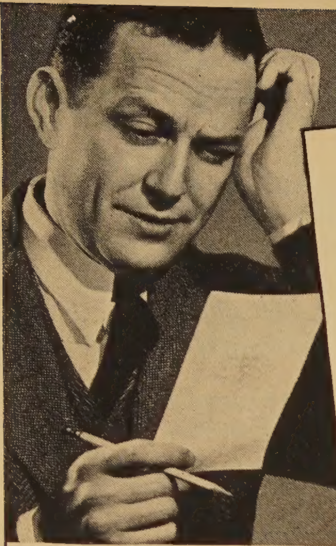

What's Your Telephone Score?

EVERY DAY many pleasant voices go over the telephone. And it seems to us the number is growing. For most people realize the business and social value of "The Voice with a Smile."

Sometimes what may appear like a gruff or hasty manner is not meant that way at all, but is simply carelessness or thoughtlessness.

Since this is the age of quizzes, how about a short one on some points of telephone usage?

Do You Talk Directly Into the Telephone?

The proper way to use the telephone for best results is to hold the transmitter directly in front of the lips while you are talking.

Do You Speak Pleasantly?

Remember . . . it may be your best friend or best customer. Greet him as pleasantly as if you were face to face. Pleasant people get the most fun out of life anyway.

Do You Hang Up Gently?

Slamming the receiver may seem discourteous to the person to whom you have been talking. You don't mean it, of course, but it may leave the wrong impression.

Do You Talk Naturally?

Your normal tone of voice is best. Whispered words are indistinct. Shouting distorts the voice and may make it gruff and unpleasant.

Do You Answer Promptly?

Most people do. Delay in answering may mean that you miss an important call. The person calling may decide that no one is there and hang up.

"The Voice with a Smile"

can be a real asset. Haven't you often said of some one who has just telephoned — "My, but she has a pleasant voice." Or — "I like to do business with them because they are so nice over the telephone."

It's contagious too. When some one speaks pleasantly to you, it's easy to answer in the same manner.

Many times you form your impression of people—and they judge you — by the sound of a voice over the telephone.

BELL TELEPHONE SYSTEM

THE BELL SYSTEM CORDIALLY INVITES YOU TO VISIT ITS EXHIBITS AT THE NEW YORK WORLD'S FAIR AND THE GOLDEN GATE INTERNATIONAL EXPOSITION, SAN FRANCISCO

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